5-1991

Estimation of Crop Evapotranspiration by Means of the Penman-Monteith Equation

Paul J. Vanderkimpen
Utah State University

1-1-1991

Estimation of Crop Evapotranspiration by means of the Penman-Monteith Equation

Paul J. Vanderkimpen
Utah State University

ESTIMATION OF CROP EVAPOTRANSPIRATION

BY MEANS OF

THE PENMAN-MONTEITH EQUATION

by

Paul J. Vanderkimpen

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Agricultural and Irrigation Engineering

Approved:

Richard G. Allen Major Professor	Robert W. Hill Committee Member
Lawrence E. Hipps Committee Member	Christopher M. Neale Committee Member
James L. Wright Committee Member	James P. Shaver Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

1991

ACKNOWLEDGEMENTS

I wish to thank my advisor, Dr. R.G. Allen and the members of my committee, Dr. R.W. Hill, Dr. L.H. Hipps, Dr. C.M. Neale and Dr. J.L. Wright for their guidance and encouragement throughout the course of my research. A special word of thanks goes to Dr. J.L. Wright for making his unique data sets available for this study.

I also wish to express my gratitude to the various institutions who have financially supported my studies and research: the Belgian American Educational Foundation (through a Fellowship received during the academic year 1987-1988), the Utah Agricultural Experiment Station (through Project 804), the Agricultural Research Service of the United States Department of Agriculture (through Agreement No 58-91H2-0-344) and the Graduate School at Utah State University (through a Research Vice President Fellowship received during the academic year 1990-1991).

Paul Vanderkimpen,

August 1991.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Symbol	Definition	Units
a_b	empirical constant	$m\ s^{-1/2}$
a_c	empirical constant	$s\ m^{-1}$
a_e	empirical constant	-
a_r	empirical constant	-
a_s	empirical constant	$s\ m^{-1}$
a_w	empirical constant	-
AM	available soil moisture	%
b_e	empirical constant	$kPa^{-1/2}$
b_c	empirical constant	$m^3\ J^{-1}$
b_r	empirical constant	-
b_s	empirical constant	$s\ m^{-1}$
b_w	empirical constant	$s\ m^{-1}$
B^{-1}	inverse surface sublayer Stanton number	-
c_c	empirical constant	$m^3\ J^{-1}$
c_s	empirical constant	-
C_p	specific heat of moist air at constant pressure	$J\ kg^{-1}\ K^{-1}$
C_{pd}	specific heat of dry air	$J\ kg^{-1}\ K^{-1}$
C_{pw}	specific heat of water vapor	$J\ kg^{-1}\ K^{-1}$
C_s	soil heat coefficient	$W\ m^{-2}\ {}^\circ C^{-1}$
D	day of the year	-
d_{est}	estimated zero plane displacement for momentum	m
d_m	zero plane displacement for momentum	m
d_r	relative distance of the earth from the sun	-
d_s	zero plane displacement for scalars	m
D_w	diffusivity of water vapor in air	$m^2\ s^{-1}$
e_a	actual vapor pressure of the air	kPa
e_0	vapor pressure at the effective surface	kPa
e^0	saturation vapor pressure	kPa
e_s	saturation vapor pressure of the air	kPa
E	latent heat flux	$W\ m^{-2}$
E_m	measured evaporation	$mm\ day^{-1}$
E_p	potential evaporation	$mm\ day^{-1}$
ET_c	crop evapotranspiration	$W\ m^{-2}$, $mm\ day^{-1}$
ET_m	measured evapotranspiration	$W\ m^{-2}$, $mm\ day^{-1}$
ET_r	reference evapotranspiration	$W\ m^{-2}$, $mm\ day^{-1}$

f_c	fraction of soil surface covered by plants	-
f_w	fraction of soil surface wetted by rain or irrigation	-
g	gravitational acceleration	$m\ s^{-2}$
G	soil heat flux	$W\ m^{-2}$
G_{sc}	solar constant	$W\ m^{-2}$
h	crop height	m
H	sensible heat flux	$W\ m^{-2}$
i	intercept of wind speed versus logarithm of height curve	-
k	von Karman constant	-
K_a	soil moisture availability factor	-
K_c	crop coefficient	-
K_{cb}	basal crop coefficient	-
K_K	eddy diffusivity attenuation coefficient	-
K_R	radiation extinction coefficient	-
K_{Rn}	net radiation extinction coefficient	-
K_{Rs}	solar radiation extinction coefficient	-
K_s	wet soil evaporation term	-
K_u	wind speed attenuation coefficient	-
l	thickness of dry top soil layer	m
LAI	leaf area index	$m^2\ m^{-2}$
LAI_{dc}	leaf area index of a dense crop	$m^2\ m^{-2}$
LAI_{eff}	effective leaf area index	$m^2\ m^{-2}$
LAI_{max}	maximum leaf area index for a fully developed crop	$m^2\ m^{-2}$
LAI_{gr}	green leaf area index	$m^2\ m^{-2}$
LAI_{gm}	maximum green leaf area index	$m^2\ m^{-2}$
N	number of measurements	-
p	porosity of top soil	$m^3\ m^{-3}$
P	atmospheric pressure	kPa
PM_c	sub-model for closed canopy	$W\ m^{-2}$
PM_s	sub-model for bare soil	$W\ m^{-2}$
P^o	standard atmospheric pressure	kPa
q	specific humidity of the air	$kg\ kg^{-1}$
q'	instantaneous deviation from the average specific humidity	$kg\ kg^{-1}$
r_a	aerodynamic resistance	$s\ m^{-1}$
r_a'	computed aerodynamic resistance not corrected for atmospheric stability	$s\ m^{-1}$
r_a''	computed aerodynamic resistance corrected for atmospheric stability	$s\ m^{-1}$

r_{aa}	aerodynamic resistance	$s\ m^{-1}$
r_{ac}	bulk boundary layer resistance	$s\ m^{-1}$
r_{ah}	aerodynamic resistance to heat	$s\ m^{-1}$
r_{am}	aerodynamic resistance to momentum	$s\ m^{-1}$
r_{as}	within canopy transfer resistance	$s\ m^{-1}$
r_{aw}	aerodynamic resistance to water vapor	$s\ m^{-1}$
r_b	leaf boundary layer resistance	$s\ m^{-1}$
r_l	leaf resistance	$s\ m^{-1}$
r_{la}	average leaf resistance	$s\ m^{-1}$
r_{lc}	leaf cuticular resistance	$s\ m^{-1}$
r_{ls}	sunlit leaf resistance	$s\ m^{-1}$
r_s	surface resistance	$s\ m^{-1}$
r_{si}	hourly surface resistance	$s\ m^{-1}$
r_{sa}	arithmetic average surface resistance	$s\ m^{-1}$
r_{sc}	plant resistance	$s\ m^{-1}$
r_{sh}	harmonic average surface resistance	$s\ m^{-1}$
r_{ss}	soil resistance	$s\ m^{-1}$
R_a	extraterrestrial radiation	$W\ m^{-2}$
R_b	net longwave radiation	$W\ m^{-2}$
R_{bo}	clear sky net longwave radiation	$W\ m^{-2}$
R_d	specific gas constant for dry air	$J\ kg^{-1}\ K^{-1}$
Ri	discrete approximation of the gradient Richardson number	-
Ri_{avg}	average Richardson number for the surface air layer	-
Ri_m	measured Richardson number	-
RMSE	root mean squared error	f(var)
R_n	net radiation	$W\ m^{-2}$
R_{ns}	net radiation received at the surface	$W\ m^{-2}$
R_s	solar radiation	$W\ m^{-2}$
R_{so}	clear sky solar radiation	$W\ m^{-2}$
s	slope of wind speed versus logarithm of height curve	$s\ m^{-1}$
t	tortuosity factor	-
t_d	number of days required for the soil surface to dry completely after wetting	days
t_w	number of days since last wetting	days
T	temperature	°C
T_a	air temperature	°C, K
T_{dew}	dewpoint air temperature	°C
T_{max}	maximum air temperature	°C, K
T_{min}	minimum air temperature	°C, K
T	temperature at the effective surface	°C
T^8	standard temperature	K
T_p	mean air temperature for the preceeding 3 days	°C
T_v	virtual temperature	K
T_{vo}	virtual temperature at the effective surface	K
T_{v2}	virtual temperature at 2 m	K

T_{v3}	virtual temperature at 3 m	K
T_0	surface temperature	K
T_1	air temperature at 1 m	K
T_2	air temperature at 2 m	K
T'	instantaneous deviation from the average air temperature	K
u_a	wind speed at level a	$m\ s^{-1}$
u_b	wind speed at level b	$m\ s^{-1}$
u_c	wind speed at level c	$m\ s^{-1}$
u_o	wind speed at the effective surface	$m\ s^{-1}$
u_z	wind speed at height z	$m\ s^{-1}$
u_1	wind speed at 1 meter	$m\ s^{-1}$
u_2	wind speed at 2 meters	$m\ s^{-1}$
u_3	wind speed at 3 meters	$m\ s^{-1}$
u'	instantaneous deviation from the average horizontal wind speed	$m\ s^{-1}$
u_*	friction velocity	$m\ s^{-1}$
w_i	weighing factor	-
w_l	leaf width	m
w'	instantaneous deviation from the average vertical wind speed	$m\ s^{-1}$
W_f	wind function	-
z	height of measurement	m
z_a	height of wind speed level a	m
z_b	height of wind speed level b	m
z_c	height of wind speed level c	m
z^{δ}	standard elevation	m
z_{om}	roughness length for momentum	m
z_{om}'	roughness length for momentum of a bare soil	m
z_{os}	roughness length for scalars	m
z_s	site elevation	m
α	atmospheric adiabatic lapse rate	$K\ m^{-1}$
α_c	plant albedo	-
α_{cs}	albedo of a crop-soil mixture	-
α_r	reference crop albedo	-
α_s	soil albedo	-
α_{sd}	fully dry soil albedo	-
α_{sm}	moist soil albedo	-
α_{sw}	fully wet soil albedo	-
γ	psychrometric constant	$kPa\ K^{-1}$
δ	solar declination	rad
Δ	slope of saturation vapor pressure versus temperature curve	$kPa\ K^{-1}$

ε	ratio of molecular weights of water vapor and dry air	-
Θ	volumetric soil moisture content	$m^3\ m^{-3}$
Θ_{sat}	saturation soil moisture content	$m^3\ m^{-3}$
λ	latent heat of vaporization	$J\ kg^{-1}$
ρ_a	density of moist air	$kg\ m^{-3}$
σ	Stefan-Boltzman constant	$W\ m^{-2}\ K^{-4}$
τ	momentum flux	$N\ m^{-2}$
φ	latitude	rad
ϕ_m	gradient stability correction function for momentum	-
ϕ_s	gradient stability correction function for scalars	-
Φ_m	average stability correction function for momentum	-
Φ_s	average stability correction function for scalars	-
Ψ_m	integrated stability correction function for momentum	-
Ψ_s	integrated stability correction function for momentum	-
ω_s	sunset hour angle	rad

ABSTRACT

Estimation of Crop Evapotranspiration
by means of
the Penman-Monteith Equation

by

Paul J. Vanderkimpen, Doctor of Philosophy
Utah State University, 1991

Major professor: Dr. Richard G. Allen
Department: Agricultural and Irrigation Engineering

This study evaluated the potential of using simple, semi-empirical resistance models for the direct estimation of crop evapotranspiration as an alternative to the traditional approach involving a reference equation and a crop coefficient. It consisted of three major parts.

The first part originally aimed at the development of simple expressions for the aerodynamic and surface resistance terms in the Penman-Monteith equation. This goal could not be achieved because of two reasons: First, the determination of aerodynamic resistance was rendered impossible because of problems with the measurements, and, secondly, the values of surface resistance, back-calculated from the Penman-Monteith equation, turned out to be very sensitive to the estimates of aerodynamic resistance.

In the second part, two forms of the Penman-Monteith equation and one form of the Shuttleworth-Wallace model were compared to each other and to the traditional Kimberly-Penman approach. The analysis showed that (1) it was possible to fit a simple form of the Penman-Monteith equation to measured data, (2) one form of the Penman-Monteith equation allowed a better fit than the Kimberly-Penman approach and (3) the Shuttleworth-Wallace model provided a slightly better fit to the data than the Penman-Monteith equation.

In the third part, the possibility of estimating net radiation and soil heat flux was investigated and a comparison was made between meteorological observations obtained at a grassed weather station and those obtained above an agricultural crop. The results indicated that (1) it was difficult to obtain an accurate estimate of net radiation or soil heat flux for a partial canopy and (2) major differences existed between measurements of vapor pressure deficit and wind speed obtained above an agricultural crop and at a grassed weather station.

From the analysis, it is concluded that the benefit of using a semi-empirical form of the Penman-Monteith equation instead of the traditional approach is limited, in particular for the prediction of crop evapotranspiration from limited historical measurements executed at a grassed weather station. As an alternative, the use of an elaborate multi-layer model for the determination of more versatile crop coefficients is suggested. (263 pages)

CHAPTER I

INTRODUCTION

Background

In today's world, a rapidly growing world population is placing an ever increasing pressure on the earth's limited resources. Of those resources, water is among the most precious: its availability directly determines man's ability to survive.

Though plentiful in humid areas, water is a very scarce resource in arid and semi-arid regions. It is therefore paramount that the little water available in those areas be used in an optimal, non-wasteful manner, to the benefit of as many people possible.

One of the largest consumers of water in arid regions undoubtedly is irrigated agriculture. Large amounts of water need to be applied to the land to sustain plant growth in a hostile environment. Knowing just how much water to apply and when exactly to do so may very well become a matter of survival.

The agronomic consequences of improper water applications are well known: underirrigation causes reduced growth and loss of yield, whereas overirrigation often leads to waterlogging, salinization, leaching of nutrients and groundwater degradation.

The effects of inadequate water management can, however, reach far beyond agronomy. Arid regions in developing countries are often characterized by fragile economies and subsistence agriculture. Under such conditions, local water shortages (possibly caused by wastage elsewhere) and the resulting harvest failures can easily trigger migration and other complex social problems. In the long run, improper irrigation may also bring about irreversible salinization and hence the permanent destruction of once prosperous agricultural areas. Finally, a correct assessment of agricultural water needs also allows diversion of excess water to other uses and helps to avoid overspending on irrigation infrastructure with unnecessarily large capacities. The water and funds made available in this way can then further contribute to overall regional development.

Statement of the Problem

During the latter half of this century, major progress has been made towards understanding and quantifying the process of evapotranspiration (i.e. the loss of water from vegetated land by a combination of transpiration by plants and evaporation from the underlying soil). The research efforts of many pioneers have led to a number of practical equations that allow the estimation of evapotranspiration. Most of these well-known equations carry the names of their developers: the Thornthwaite equation (Thornthwaite, 1948), the Penman equation (Penman, 1948), the Blaney-Criddle equation (Blaney and Criddle, 1950), the Jensen-Haise equation (Jensen and Haise, 1963), the Priestley-Taylor equation (Priestley and Taylor, 1972), the Hargreaves equation (Hargreaves, 1975) and others.

Almost all of these equations have two major problems in common. First, they are empirical or semi-empirical in nature. In other words, they contain a number of constants or functions that need to be determined by calibration. Secondly, most of these equations produce estimates of evapotranspiration from a well-watered reference crop or a free water surface only. In order to compute the water use by a specific crop, the reference evapotranspiration often needs to be multiplied by a crop coefficient. This empirical coefficient masks all the physical differences between the reference crop and the specific crop under consideration and is obtained by measurements of actual crop evapotranspiration. It thus reflects the specific behavior of a single crop under particular cultural practices. This dual need for calibration reduces the transferability of the aforementioned equations and limits their reliable application to the regions and conditions for which they were originally developed. Ideally, both the reference equation and the crop coefficient should be recalibrated locally prior to use. In practice, however, one usually settles for the available literature values.

Monteith (1965) derived an alternative form of the Penman equation, on the basis of an electrical analogue.

Shuttleworth and Wallace (1985) used this equation as the basis for a more elaborate model. Both models are physically based and, providing the proper values for the resistances involved are inserted, they can be used to directly predict water use by any crop. Unfortunately, the exact expressions for those resistances are complex in nature and their computation requires detailed measurements which tends to limit the application of these models to research sites. As a result, additional research focussing on the development of practical expressions for the required resistances is needed to render resistance models useful for engineering applications.

Objectives

(1) Primary objective

To establish operational expressions for the resistance terms in the Penman-Monteith equation, allowing the use of this equation for the direct estimation of crop evapotranspiration from a well-watered agricultural crop at any stage of growth. This objective includes the development of methods to incorporate the effect of wet soil evaporation during the early stages of crop development. Specific attention will be given to a row crop (beans) and a drilled crop (wheat).

(2) Secondary objectives

(a) To evaluate the performance of the Penman-Monteith model developed under (1) by comparing its predictions to those from a traditional model (Kimberly-Penman equation in combination with a crop coefficient).

(b) To evaluate the benefits of using a more elaborate model such as the Shuttleworth-Wallace model.

(c) To develop an algorithm that will allow the estimation of net radiation and soil heat flux during all stages of growth, whenever measured values of these variables are not available.

Scope of Study

Resistance models for evapotranspiration have been implemented in a large number of forms and on a wide range of temporal and spatial scales. This study focusses on two simple resistance models, namely the single-layer Penman-Monteith model and the two-layer Shuttleworth-Wallace model. Other, more complex, multi-layer models are not considered.

Resistance models have been applied to a large number of surface conditions ranging from bare desert soils to tropical forests. This study is limited to well-watered agricultural crops throughout the entire growing season. The specification "well-watered" implies that the effects of soil moisture stress are not addressed.

Most attention is given to the bulk exchanges between large homogenous fields and the overlying surface boundary layer. Whenever exchanges between individual leaves and their environment need to be taken into consideration, they are dealt with in a very simplified manner.

Most emphasis is placed on the daily time scale. Because of data resolution, hourly exchanges are studied less intensively.

Throughout the text, it will be assumed that the reader is already familiar with standard micro-meteorological concepts and the related terminology.

CHAPTER II

LITERATURE REVIEW

Historical Development

The evapotranspiration of water from natural surfaces requires two essential components: a source of energy and a vapor transport mechanism. The source of energy is needed to provide the latent heat of vaporization required to bring about a phase change from liquid water to water vapor. The vapor transport mechanism, on the other hand, is necessary to continuously move the water vapor away from the surface and thus maintain a vapor pressure gradient between the evaporating surface and the surrounding air.

Up to the middle of this century, evapotranspiration was studied solely in terms of one of these mechanisms. The corresponding computational techniques became known as the Energy Balance method and the Mass Transport or Bulk Aerodynamic method. In the first method, evapotranspiration is obtained as the residual of net radiation, sensible heat and soil heat flux. In the second approach, it is quantified by means of an empirical relationship based on the Dalton equation. More detailed discussions of these techniques are given by Brutsaert (1982) and Rosenberg et al. (1983).

Penman (1948) was the first to combine both approaches into what is now commonly referred to as the Combination method. The main merit of this Combination method is that it only requires knowledge of a number of commonly observed meteorological variables at a single level.

The original Penman equation (Penman, 1948) contained an empirical wind function and was intended for the estimation of evaporation from a free water surface. Penman (1948) also suggested that the evapotranspiration from a short green turf could be approximated by multiplying the evaporation from a free water surface with an empirical constant ranging from 0.6 to 0.8 depending on the time of year. Penman and Shofield (1951) made an attempt to explain this empirical factor on the basis of stomatal behavior. For this purpose, Penman (1952) modified his original equation and introduced a stomatal factor (reflecting stomatal geometry) and a day length factor (accounting for stomatal closure). He believed that this new equation would be applicable to any short green crop. For taller crops, Penman (1952) recommended the use of a modified wind function.

Businger (1956) suggested that differences in surface roughness could be accounted for by replacing the empirical wind function by a theoretical expression based on a logarithmic wind speed profile. He also pointed out the need for an atmospheric stability correction to this expression. Businger (1956) further suggested to replace Penman's stomatal factor and day length factor by a single empirical factor, the magnitude of which was obtained by calibration.

Tanner and Pelton (1960) tested a formula that incorporated Penman's stomatal and day length factors, as well as Businger's theoretical wind function, on an alfalfa-brome grass mixture. They recommended the use of Businger's wind function, but found no benefit in using any correction for stomatal control of evapotranspiration. These findings were later confirmed by Van Bavel (1966) for free water, wet soil and alfalfa.

McIlroy (Slatyer and McIlroy, 1961) derived a generalized form of the combination equation, also applicable to non-saturated surfaces. It did, however, require a measurement of wet bulb depression at the surface. Working along the same lines, Penman (1961) proposed yet another version of his formula that featured Businger's wind function and required an additional measurement of within-canopy relative humidity. This formula was deemed applicable to any surface.

Penman (1963), however, returned to the original form (Penman, 1948), but suggested a new calibration of the empirical wind function to allow the direct computation of evapotranspiration from a short, green, well-watered grass reference crop. It is this formula which is usually referred to as the Penman equation. Since the time of its first publication, various authors (e.g. Doorenbos and Pruitt, 1977; Wright, 1982) have proposed alternative wind function calibration factors for use with grass or alfalfa reference crops growing under specific conditions.

Monteith (1965) derived a new version of the Penman equation, on the basis of an electrical analogue. His equation is entirely physically based and contains two resistance terms. The aerodynamic resistance replaces the empirical wind function and is essentially the same as Businger's wind function, whereas the surface resistance substitutes Penman's stomatal and day length factors. In time, Monteith's version of the Penman equation has become known as the Penman-Monteith equation.

Although the Penman-Monteith equation is suitable for different types of crops, it has one major limitation: because it represents a single-layer approach, its application should preferably be limited to homogeneous canopies fully shading the ground. Shuttleworth and Wallace (1985) recognized this shortcoming and, on the basis of the Penman-Monteith equation, they developed a more elaborate two-layer model, capable of distinguishing between transpiration from plants and evaporation from the underlying or surrounding soil. This model is specifically intended for use with sparse canopies and will be designated as the Shuttleworth-Wallace model.

Single-Layer Models

Single-layer models are models that treat the vegetated surface as consisting of a single layer. All exchange processes (heat, mass and momentum) between this vegetation layer and the overlying atmosphere are studied in the form of bulk exchanges, which are assumed to take place in a hypothetical plane, usually located at about three fourths of the canopy height (see next chapter for more details). Resistance models that fall into this category are those of Monteith (1965), Rijtema (1965) and Brown and Rosenberg (1973).

From the time they were first proposed, single-layer models have been heavily criticized by various authors (Tanner, 1963; Philip, 1964; Philip, 1966, Tanner and Fuchs, 1968). These authors emphasized the differences in the locations of sources and sinks for water vapor, sensible heat and momentum inside a plant canopy. In addition, they pointed out that exchange processes in such a canopy are distributed over the entire volume of the canopy and cannot be concentrated into a single exchange plane. Some did add, however, that "...[such a method] is worth testing because of its simplicity..." (Tanner, 1963, p. 148) and "...may prove to have empirical engineering convenience..." (Tanner and Fuchs, 1968, p. 1303).

The exact form of the model proposed by Monteith (1965) will be discussed in detail in the next chapter. It was developed for use with homogeneous canopies and Monteith (1965) illustrated its use for various crops. Soon afterwards, the model was applied to alfalfa by Van Bavel

(1967) and to open water, alfalfa, potatoes and pine forest by Szeicz et al. (1969). By now, the use of the Penman-Monteith equation has become widespread and numerous applications can be found in the literature. Examples of applications to agricultural crops are given by Nkemdirim (1976) for potatoes, Russell (1980) for barley and pasture and Van Zyl and De Jager (1987) for wheat. In spite of a wide variety of assumptions made during the actual implementation of the model (some of which are no longer considered acceptable), most authors have reported very good results.

Allen (1986) and Allen et al. (1989) compared various forms of the Penman equation and concluded that Monteith's version was superior to others when applied to reference grass and alfalfa.

Shuttleworth (1976a) contended that the Penman-Monteith equation is not applicable to canopies partially wetted by precipitation. In a rebuttal, Monteith (1977) pointed out some flaws in Shuttleworth's analysis and proved that his equation holds for partially wetted canopies too, providing the proper surface resistance is used.

Monteith (1981) repeated that his model was intended for use with fully developed homogenous canopies and is not applicable to row crops partially shading the soil. For such crops, he recommended the use of the empirical schemes developed by Ritchie (1972) and Tanner and Jury (1976).

In spite of the original intention, many researchers have modified Monteith's model and applied it to crops with an incomplete cover. Black et al. (1970) adjusted the model by explicitly including an empirical soil evaporation component and tested the new version for snap beans. They found that the new model slightly overestimated crop evapotranspiration measured by lysimeter and attributed this to the inaccuracy of the evaporation component. Brun et al. (1972) applied the modified model to soybeans and sorghum, after altering its evaporation component. They reported that the new version was in agreement with lysimetric measurements, except under conditions of high atmospheric demand when the model underestimated evapotranspiration. Grant (1975) incorporated wet soil evaporation by replacing the original surface resistance by a plant resistance and a soil resistance, both of which were assumed to be acting in parallel and used the new model to compute evapotranspiration from wheat. Thompson et al. (1981) modified this approach and applied it to a large number of agricultural crops, including pasture, wheat, potatoes and sugar beets. Both Grant (1975) and Thompson et al. (1981) evaluated their models by means of neutron probe measurements of soil moisture deficit and concluded that the predictions were in good agreement with the measurements.

The model proposed by Rijtema (1965) is essentially the same as that of Monteith (1965). The main difference lies in the evaluation of the aerodynamic resistance: Monteith utilized the theoretical relationship derived by Businger (1956), whereas Rijtema developed an alternative empirical function, also based on the logarithmic wind profile parameters. Rijtema's original model (Rijtema, 1965) was calibrated for use with a homogeneous grass cover. It was later modified (Rijtema and Ryhiner, 1966; Rijtema, 1968) to incorporate the effects of incomplete cover and evaporation of intercepted rainfall. The modified model was tested for wheat (Rijtema and Ryhiner, 1966) and potatoes (Endrodi and Rijtema, 1969). Later on, it was applied to a number of vegetables by Feddes (1971) and to a variety of field crops by Slabbers (1977). Feddes (1971) and Slabbers (1977) both concluded that the model predictions were in reasonable agreement with soil water balance computations.

The model developed by Brown and Rosenberg (1973) features the same resistances as the models proposed by Monteith (1965) and Rijtema (1965), but requires an iterative solution and is only applicable to surfaces with a full canopy cover. Brown and Rosenberg (1973) used their model to estimate water use of sugar beets and found that the results agreed to within 5 % with evapotranspiration computed from the energy balance equation. Verma and Rosenberg (1977) simplified the model by introducing functional relationships for both resistances and tested the new version on a sorghum field. They reported that the simplified model agreed to within 10 % with lysimetric and Bowen ratio measurements of evapotranspiration.

The aerodynamic resistance implemented by Rijtema (1965) appears to be less rigorous than the one used by Monteith (1965). The model proposed by Brown and Rosenberg (1973), on the other hand, has a smaller application field and seems unnecessarily cumbersome because of its iterative solution. As a result, this study will focus entirely on Monteith's model, more specifically, the expanded versions deemed applicable to incomplete canopies.

Multi-Layer Models

Contrary to the single-layer models, multi-layer models do take the spatial distribution of sources and sinks in a plant canopy into account. This is achieved by subdividing the canopy - and sometimes also the underlying soil - into a number of layers, each with its own properties. In these models, two different processes are studied explicitly: exchanges between a leaf and the surrounding air and transfers from one layer into the next, through the canopy air space.

One of the earliest multi-layer resistance models was that of Waggoner and Reifsnyder (1968). It was only applicable to homogenous, fully developed vegetation and was used to simulate the microclimate of red clover and barley. It was later expanded by Goudriaan and Waggoner (1972), who added a soil simulation module describing evaporation from the soil underneath a full vegetative cover. More recent models are also capable of dealing with incomplete canopies. An example is the model of Jagtap and Jones (1989a), which was developed for use with soybeans. Jagtap and Jones (1989b) used this model to study the stability of crop coefficients under different climates and irrigation management practices. They concluded that significant errors in the estimate of seasonal evapotranspiration could occur when crop coefficients developed under one set of conditions were used under different climate and management conditions.

Many multi-layer models have two problems in common. First, they require a vast amount of detailed data, usually not available to the practicing engineer and secondly, their application often also requires the iterative solution of a large implicit system of equations.

The second problem was addressed by Chen (1984) and Lhomme (1988a). Chen (1984) proposed to replace the fluxes of latent and sensible heat, which are coupled and thus lead to a system of implicit equations, by two new variables: the enthalpy flux and the saturation heat flux. These new entities are uncoupled and produce equations that can be solved explicitly. Lhomme (1988a), on the other hand, presented an approach that retains the original fluxes but still arrives at explicit expressions for the sensible and latent heat fluxes above the canopy.

Many authors have recognized the first problem and have looked into the validity of using simplified, more manageable models. Sinclair et al. (1976) compared an elaborate multi-layer model to a simplified version and to the Penman-Monteith model. They concluded that the Penman-Monteith approach offered substantial potential for the conditions investigated but that additional work is required to assess the universality. Shuttleworth (1976b) started out with a continuous multi-layer model of closed vegetation, which he subsequently rewrote in terms of a single-layer equivalent. A comparison of this single-layer equivalent to the Penman-Monteith model revealed the assumptions underlying the latter. Shuttleworth (1978) expanded this approach to include wet and partially wet canopies and Shuttleworth (1979) incorporated the effects of below-canopy fluxes. Lhomme (1988b) followed the same approach but started from a discrete multi-layer model and arrived at an alternative theoretical comparison of multi-layer and single-layer models.

In recent years, a number of strongly simplified multi-layer models have been proposed (Katerji and Perrier, 1985; Shuttleworth and Wallace, 1985; Choudhury and Monteith, 1988). All of these models are essentially of a two-layer nature: they recognize only two different sources (or sinks), namely the plants and the soil. All of these two-layer models are capable of distinguishing evaporation from transpiration and feature the same set of resistances.

Katerji and Perrier (1985) used their model to study the relative importance of the various resistances in an alfalfa crop as a function of soil moisture, stomatal resistance and leaf area index. They showed that the error introduced by neglecting wet soil evaporation becomes negligible as soon as leaf area index exceeds a minimum value.

Shuttleworth and Wallace (1985) originally presented a theoretical study of the energy partition in sparse crops. They developed a model to predict the relative magnitude of evaporation and transpiration in a sparse crop as a function of leaf area index and soil moisture conditions. The study showed that the fractional contribution of transpiration to total evapotranspiration increases as leaf area index increases and soil moisture decreases. Later on, the Shuttleworth-Wallace model was tested for subarctic wetland (Lafleur and Rouse, 1990) and dryland millet (Wallace et al. 1990). Lafleur and Rouse (1990) tested both the original Penman-Monteith model and the Shuttleworth-Wallace model. They observed that the predictions of evapotranspiration by means of the Shuttleworth-Wallace model were in excellent agreement with measurements made by the Bowen ratio technique. This was true throughout the entire growing season, with surface conditions ranging from non-vegetated to fully vegetated. The Penman-Monteith model, on the other hand, underestimated evapotranspiration in the early stages of development, because it did not account for the substantial evaporation during that time. From these observations, Lafleur and Rouse (1990) concluded that the Shuttleworth-Wallace model was clearly superior to the Penman-Monteith model, especially in the early stages of vegetation growth when the leaf area index was low. Wallace et al. (1990) computed evapotranspiration from sparse dryland millet by means of the original Penman-Monteith model and the Shuttleworth-Wallace model. The comparison showed that the Penman-Monteith equation underestimated evapotranspiration when the soil surface was dry and overestimated it when the soil surface was wet. Wallace et al. (1990) attributed these differences to the modification of the in-canopy vapor pressure deficit by heat and vapor fluxes from the soil. This process is accounted for by the Shuttleworth-Wallace model, but not by the Penman-Monteith model.

Choudhury and Monteith (1988) used their model to simulate the microclimate and evapotranspiration of a wheat crop. They concluded that the general implications of the model were consistent with observations and that the estimates of evapotranspiration agreed well with lysimetric measurements.

In this study, only the two-layer Shuttleworth-Wallace model will be evaluated. It was chosen over other models because it is strongly related to the Penman-Monteith equation and because it offers an explicit analytical solution.

CHAPTER III

THEORY

The Kimberly-Penman Model

General Approach

The Kimberly-Penman equation is a version of the Penman equation developed by Wright (1982) at Kimberly, Idaho. It is a combination equation of the semi-empirical type: it contains an empirical wind function which was calibrated for an alfalfa reference crop growing under arid conditions with considerable regional advection. The equation predicts reference evapotranspiration from alfalfa on a daily basis. Daily crop evapotranspiration from a number of common agricultural crops can subsequently be obtained by multiplying this reference evapotranspiration by an empirical crop coefficient.

Since this method was developed and calibrated at the site under study, it yields highly accurate results for this location. Therefore, it was used as a reference to which the various resistance models were compared.

The reference equation and the corresponding crop coefficients were first presented by Wright (1982). An updated version was given in Jensen et al. (1990). Most of the material presented in this section was drawn from these two sources.

Reference Evapotranspiration

The general form of the Kimberly-Penman equation is:

$$ET_r = \frac{\Delta\ (R_n - G) + \gamma\ 74.4\ W_f\ (e_s - e_a)}{\Delta + \gamma} \qquad (1)$$

where ET_r = reference evapotranspiration (W m^{-2}), R_n = net radiation (W m^{-2}), G = soil heat flux (W m^{-2}), W_f = wind function, e_s = saturation vapor pressure of the air (kPa), e_a = actual vapor pressure of the air (kPa), Δ = slope of saturation vapor pressure versus temperature curve (kPa K^{-1}), γ = psychrometric constant (kPa K^{-1}) and 74.4 is a unit conversion factor.

The empirical wind function W_f has the form:

$$W_f = a_w + b_w\ u_2 \qquad (2)$$

where a_w, b_w = empirical constants and u_2 = daily average wind speed at 2 m (m s^{-1}). The constants a_w and b_w can be obtained from:

$$a_w = 0.4 + 1.4\ \exp\{-[(D-173)/58]^2\} \qquad (3)$$

and

$$b_w = 0.605 + 0.345\ \exp\{-[(D-243)/80]^2\} \qquad (4)$$

where D = day of the year (1-366). The wind speed should be measured at a height of 2 m above short clipped grass. When wind speed was measured at a height other than 2 m, it can be converted into a 2 m equivalent by means of the following power law:

$$u_2 = u_z \ (2/z)^{0.2} \tag{5}$$

where u_z = measured wind speed (m s^{-1}) and z = height of measurement (m).

The saturation vapor pressure can be related to temperature by means of (Tetens, 1930):

$$e^o = \exp[(16.78\ T - 116.9)/(T + 237.3)] \tag{6}$$

where T = temperature (°C) and e^o = saturation vapor pressure at temperature T (kPa). The saturation vapor pressure e_s in the Kimberly-Penman equation can then be calculated from:

$$e_s = [e^o(T_{min}) + e^o(T_{max})]/2 \tag{7}$$

where T_{min} = daily minimum air temperature (°C) and T_{max} = daily maximum air temperature (°C), and the actual vapor pressure e_a can be estimated as:

$$e_a = e^o(T_{dew}) \tag{8}$$

where T_{dew} = dewpoint temperature measured at 8 am (°C).

By differentiating Eq. 6 with respect to T, the following expression is obtained for Δ:

$$\Delta = 4098\ e^o(T_a)/(T_a + 237.3)^2 \tag{9}$$

where T_a = average daily air temperature (°C).

When the average daily air temperature is not available, it can be approximated by:

$$T_a = (T_{min} + T_{max})/2 \tag{10}$$

The so-called psychrometric constant is defined as (Brutsaert, 1982):

$$\gamma = (C_p\ P)/(\varepsilon\ \lambda) \tag{11}$$

where C_p = specific heat of air at constant pressure (J kg^{-1} K), P = atmospheric pressure (kPa), ε = ratio of molecular weights of water vapor and dry air and λ = latent heat of vaporization (J kg^{-1}). The constant ε has a value of 0.622.

The latent heat of vaporization λ can be computed as a function of temperature by means of (Harrison, 1963):

$$\lambda = (2501 - 2.361\ T_a) * 10^3 \tag{12}$$

The atmospheric pressure varies with elevation and can be estimated according to (Burman et al., 1987):

$$P = P^o\ \{[T^o - \alpha(z_s - z^o)]/T^o\}^{g/(\alpha Rd)} \tag{13}$$

where z_s = site elevation (m), α = atmospheric adiabatic lapse rate (K m^{-1}), g = gravitational acceleration (m s^{-2}), R_d = specific gas constant for dry air (J kg^{-1} K^{-1}), z^o = standard elevation (m), P^o = standard atmospheric pressure (kPa) and T^o = standard temperature (K). In the previous equation, the gravitational acceleration has a value of 9.81 m s^{-2}, the specific gas constant for dry air is equal to 287 J kg^{-1} K^{-1}. The adiabatic lapse rate α is equal to 0.0098 K m^{-1} for dry air and decreases with moisture content. Z^o, P^o and T^o equal 0 m, 101.3 kPa and 288 K respectively.

The specific heat of moist air can be obtained from (Brutsaert, 1982):

$$C_p = q\ C_{pw} + (1-q)\ C_{pd} \tag{14}$$

where C_{pd} = specific heat of dry air (J kg^{-1} K^{-1}), C_{pw} = specific heat of water vapor (J kg^{-1} K^{-1}) and q = specific humidity of the air (kg kg^{-1}). The specific heat has a value of 1005 J kg^{-1} K^{-1} for dry air at 101.3 kPa and 1846 J kg^{-1} K^{-1} for water vapor. The specific humidity is related to vapor pressure by:

$$q = \varepsilon\ e_a\ /\ (P - (1-\varepsilon)e_a) \tag{15}$$

The variation of C_p with pressure and humidity is very limited and in practice a typical value of 1013 J kg^{-1} K^{-1} is often used.

Whenever measured values for net radiation and soil heat flux are available, they can be inserted directly into the Kimberly-Penman equation. However, in engineering practice such measured values are usually not available and both net radiation and soil heat flux need to be estimated.

Daily net radiation can be estimated from solar radiation, temperature and humidity by:

$$R_n = (1-\alpha_r)\ R_s - R_b \tag{16}$$

where R_s = incoming solar radiation (W m^{-2}), R_b = net outgoing long wave radiation (W m^{-2}) and α_r = reference crop albedo.

The albedo of alfalfa varies with solar elevation and hence with time of year. On clear days ($(R_s/R_{so})>0.7$), it can be approximated by:

$$\alpha_r = 0.29 + 0.06\ \sin(D+96) \tag{17}$$

For overcast days ($(R_s/R_{so})\leq 0.7$), on the other hand, a constant value of 0.30 is assumed.

The net outgoing long wave radiation can be obtained from:

$$R_b = [a_r(R_s/R_{so}) + b_r]\ R_{bo} \tag{18}$$

where a_r, b_r = empirical constants, R_{so} = clear sky solar radiation (W m^{-2}) and R_{bo} = clear sky net outgoing long wave radiation (W m^{-2}). The values of the constants a_r and b_r also depend on weather conditions. When $(R_s/R_{so})>0.7$ then a_r = 1.126 and b_r = -0.07, but when $(R_s/R_{so})\leq 0.7$ then a_r = 1.017 and b_r = -0.06.

The clear sky solar radiation is often estimated as:

$$R_{so} = 0.75\ R_a \tag{19}$$

where R_a = extraterrestrial radiation (W m^{-2}).

Extraterrestrial radiation is a function of latitude and solar declination and is given by:

$$R_a = (1/\pi)\ G_{sc}\ d_r \quad [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \tag{20}$$

where G_{sc} = solar constant (W m^{-2}), d_r = relative distance of the earth from the sun, ω_s = sunset hour angle (rad), φ = latitude (rad) and δ = solar declination (rad). The solar constant has a value of 1367 W m^{-2} and the other variables can be obtained from:

$$d_r = 1 + 0.033 \cos(2\pi D/365) \tag{21}$$

$$\delta = 0.4093 \sin(2\pi (D+284)/365) \tag{22}$$

$$\omega_s = \arccos(-\tan(\varphi) \tan(\delta)) \tag{23}$$

The clear sky net outgoing long wave radiation, in its turn, is computed as:

$$R_{bo} = (a_e + b_e \sqrt{e_a})\ \sigma\ (T_{min}^4 + T_{max}^4)/2 \tag{24}$$

where a_e, b_e = empirical constants, σ = Stefan-Boltzman constant (W m^{-2} K^{-4}) and T_{min} and T_{max} are in K. The Stefan-Boltzman constant has a value of 5.67×10^{-8} W m^{-2} K^{-4}, b_e is equal to -0.139 $kPa^{-1/2}$ and a_e varies as:

$$a_e = 0.26 + 0.1 \exp\{-[0.0154(D-180)]^2\} \tag{25}$$

The value of the soil heat flux is usually very small on a daily basis, and when no measurements are available, this term can often be neglected. If desired, a rough estimate can be obtained from:

$$G = (T_a - T_p)\ C_s \qquad (26)$$

where T_p = mean air temperature for the preceding three days (°C) and C_s = empirical soil heat coefficient (W m^{-2} °C^{-1}). For a silt loam soil, the soil heat coefficient has a value of about 4.35 W m^{-2} °C^{-1}.

<u>Crop Evapotranspiration</u>

As indicated earlier, crop evapotranspiration is obtained by multiplying reference evapotranspiration by an empirical crop coefficient. In mathematical form:

$$ET_c = K_c\ ET_r \qquad (27)$$

where ET_c = crop evapotranspiration (W m^{-2}) and K_c = empirical crop coefficient.

The crop coefficient consists of several components:

$$K_c = K_{cb}\ K_a + K_s \qquad (28)$$

where K_{cb} = basal crop coefficient, K_a = soil moisture availability factor and K_s = wet soil evaporation term.

The basal crop coefficient reflects the evapotranspiration from a well-watered crop growing in a soil with a dry surface. Values of K_{cb} relevant to this study are listed in Table 1.

TABLE 1. Basal Crop Coefficients (after Jensen et al., 1990).

	Percent time from planting to effective cover										
Crop	0	10	20	30	40	50	60	70	80	90	100
Snap Beans	0.15	0.15	0.16	0.18	0.22	0.34	0.45	0.60	0.75	0.88	0.92
Spring Wheat	0.15	0.15	0.16	0.20	0.25	0.40	0.52	0.65	0.81	0.96	1.00
Winter Wheat	0.15	0.15	0.15	0.30	0.55	0.80	0.95	1.00	1.00	1.00	1.00

	Number of days after effective cover										
Crop	0	10	20	30	40	50	60	70	80	90	100
Snap Beans	0.92	0.92	0.86	0.65	0.30	0.10	0.05	-	-	-	-
Spring Wheat	1.00	1.00	1.00	1.00	0.90	0.40	0.15	0.07	0.05	-	-
Winter Wheat	1.00	1.00	1.00	1.00	0.95	0.50	0.20	0.10	0.05	-	-

The soil moisture availability factor accounts for the reduction in crop transpiration as the available soil moisture decreases. The wet soil evaporation term, on the other hand, incorporates the temporary increase in evaporation after the soil surface has been wetted by rain or irrigation.

Several relationships have been proposed for the soil moisture availability factor. One of those is (Jensen et al., 1970):

$$K_a = \ln(AM + 1)/\ln(101) \qquad (29)$$

where AM = available soil moisture (%). K_a ranges from 1 for a soil at field capacity to 0 for a soil at wilting point.

The wet soil evaporation factor is given by:

$$K_s = (1 - K_a K_{cb}) [1 - (t_w/t_d)^{1/2}] f_w \tag{30}$$

where t_w = number of days since last wetting, t_d = number of days required for the soil surface to dry completely after wetting and f_w = fraction of soil surface wetted by rain or irrigation. Typical values of t_d are 3 days for a sandy soil, 5 days for silt and 7 days for clay. The value of t_w is reset to 0 after each rainfall or irrigation. When t_w exceeds t_d, K_s is set equal to 0. The wetting fraction equals 1 for precipitation but can be less than 1 for some types of irrigation.

Equation 30 predicts a total amount of wet soil evaporation equal to $[0.35(t_d+1.5)(1-K_aK_{cb})f_w]$ ET_r. Whenever the total amount of rainfall or irrigation is less than this quantity, evaporation should be limited in order not to exceed the amount of water received.

The Penman-Monteith Model

General Approach

The Penman-Monteith equation is an alternative form of the Penman combination equation, based on a single-layer electrical analogue. The original Penman-Monteith equation was proposed by Monteith (1965) and was intended for use with fully developed canopies. Several authors (Jordan and Ritchie, 1971; Grant, 1975) have proposed extensions to enable its application to partial canopies. Those extended versions will be discussed here. The electrical analogue underlying the extended Penman-Monteith model is shown in Fig. 1.

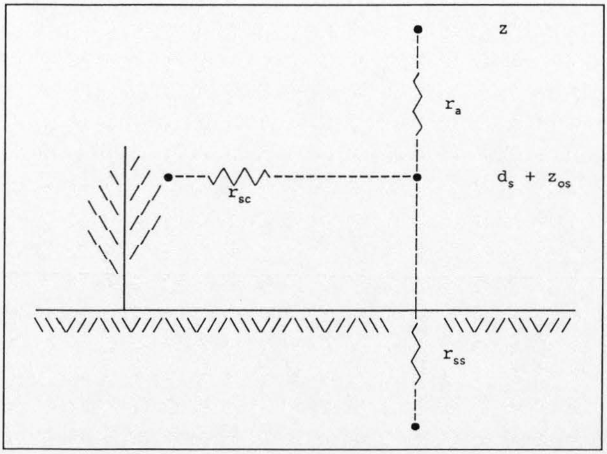

FIGURE 1. Single-Layer Electrical Analogue of the Evapotranspiration Process (after Grant, 1975).

In the electrical analogue shown in Fig. 1, the evapotranspiration process is thought of as a vapor current running from the surface into the atmosphere. This current encounters two resistances in series, a surface resistance (r_s) and an aerodynamic resistance (r_a). The surface resistance represents the resistance against vapor flow from the actual vaporization site (substomatal cavity in the case of transpiration, wet subsoil in the case of evaporation) to a hypothetical exchange plane located at about three fourths of the canopy height (the exact location will be discussed later). The aerodynamic resistance, on the other hand, is indicative of the resistance against vapor and heat transfer from this hypothetical plane into the free atmosphere, up to a given reference level. The surface resistance r_s reflects the combined effect of two other resistances, namely the plant resistance to transpiration (r_{sc}) and the soil resistance to evaporation (r_{ss}). These two resistances can be assumed to be acting in parallel.

A full derivation of the Penman-Monteith equation is given by Monteith (1965) and will not be repeated here. The final result is given by:

$$ET_c = \frac{\Delta\ (R_n - G) + \ \rho_a\ C_p\ (e_s - e_a)\ /\ r_a}{\Delta + \gamma\ (\ 1 + r_s\ /\ r_a\ )} \qquad (31)$$

where ρ_a = air density (kg m^{-3}), r_a = aerodynamic resistance (s m^{-1}) and r_s = surface resistance (s m^{-1}).

The density of moist air can be obtained from (Brutsaert, 1982):

$$\rho_a = P/(R_d\ T_a)\ [1 - (1-\varepsilon)e_a/P] \qquad (32)$$

where T_a is in K.

Contrary to the semi-empirical forms of the Penman equation, which predict reference evapotranspiration from either grass or alfalfa, the Penman-Monteith equation can be used to directly compute crop evapotranspiration from any crop. This, however, requires that all atmospheric variables be measured in the fully adjusted boundary layer above the crop under study and that the aerodynamic and surface resistances reflect the behavior of those crops. Since the fully adjusted boundary layer grows with fetch, the first requirement can be fulfilled by providing a sufficient fetch. The growth rate of a fully adjusted boundary layer depends on a variety of factors such as nature and magnitude of the change in surface conditions, surface roughness and atmospheric stability. As a general approximation, most standard texts on micrometeorology suggest a ratio of fully adjusted boundary layer thickness to fetch of 1:100 for a transition smooth-to-rough and 1:200 for rough-to-smooth. Munro and Oke (1975) showed that these ratios may be much lower for fully developed agricultural crops. In engineering practice, however, one usually wishes to predict evapotranspiration from an agricultural crop by means of meteorological measurements obtained at a weather station. The estimation of meteorological variables above an agricultural crop from measurements obtained above a different surface was addressed by McNaughton and Jarvis (1984) and Allen et al. (1989).

Aerodynamic Resistance

Definition. In this work, the term "aerodynamic resistance" (r_a) is used to indicate the resistance to the bulk exchange of a scalar property (sensible heat or water vapor) between its effective source or sink near the surface (the hypothetical exchange plane) and a given reference level in the atmosphere. The resistances to sensible heat and water vapor are assumed to be equal. In the past, some researchers (e.g. Monteith, 1965; Grant, 1975) have assumed that these resistances are also equal to the resistance to momentum transfer, but this is definitely not the case, as will be explained later.

Measurement. By manipulating the resistance expressions for the surface fluxes of momentum, heat and water vapor one obtains:

$$r_{am} = \rho_a \, (u_o - u) \; / \; \tau \qquad (33)$$

$$r_{ah} = (\rho_a \, C_p) \; (T_o - T_a) \; / \; H \qquad (34)$$

$$r_{aw} = (\rho_a \, C_p/\gamma) \; (e_o - e_a) \; / \; E \qquad (35)$$

where τ = momentum flux (N m^{-2}), H = sensible heat flux (W m^{-2}), E = latent heat flux (W m^{-2}), r_{am} = aerodynamic resistance to momentum transfer (s m^{-1}), r_{ah} = aerodynamic resistance to sensible heat transfer (s m^{-1}), r_{aw} = aerodynamic resistance to water vapor transfer (s m^{-1}), u_o = wind speed at the effective surface (m s^{-1}), T_o = temperature at the effective surface (°C) and e_o = vapor pressure at the effective surface (kPa). Equations 33 through 35 are based on the sign convention that fluxes towards the surface are negative, whereas fluxes away from the surface are positive. The quantities u_o, T_o and e_o represent the values of wind speed, temperature and vapor pressure at their effective source or sink. The wind speed at the effective surface is zero. The corresponding values of temperature and humidity can be determined by extrapolating measured profiles of temperature and humidity down to the effective surface, as proposed by Monteith (1963), Thom (1972) and Chen (1985). The surface temperature can be approximated by the radiative surface temperature, measured by means of infrared thermometry and the surface vapor pressure can be obtained from the surface temperature. In the past, various techniques have been used to determine the magnitude of surface fluxes: lysimeters, Bowen ratio and water balance for E, energy balance for H and drag plates for τ. Nowadays, all three fluxes can be measured directly by means of eddy correlation systems:

$$\tau = \rho_a \overline{u'w'} \tag{36}$$

$$H = \rho_a C_p \overline{T'w'} \tag{37}$$

$$E = \lambda \rho_a \overline{q'w'} \tag{38}$$

where u' = instantaneous deviation from the average horizontal wind speed (m s^{-1}), w' = instantaneous deviation from the average vertical wind speed (m s^{-1}), T' = instantaneous deviation from the average air temperature

(°C) and q' = instantaneous deviation from the average specific humidity (kg kg^{-1}). In Eqs. 36 through 38, the products with the overbar represent the covariance between the two variables involved. More details on the various techniques for the determination of surface fluxes can be found in Brutsaert (1982) and Rosenberg et al. (1983).

The aerodynamic resistance for scalars (water vapor or latent heat and sensible heat) differs from the aerodynamic resistance for momentum because of differences in transport mechanisms at the surface: in the free air, momentum, heat and water vapor are all transported by eddies, but at the surface, momentum is transferred by viscosity and pressure forces, whereas scalars are transported by molecular diffusion only. As a result, r_{am} is smaller than r_{ah} or r_{aw}. For bluff surface elements, the effect of pressure forces is more important than for permeable surface elements. Therefore, the difference between r_{am} and r_{ah} or r_{aw} is larger for bluff surfaces than for permeable surfaces. The difference between r_{ah} and r_{aw} is usually neglected. In summary, we can say: $r_{am} < r_{ah} \approx r_{aw} \approx r_a$.

<u>Prediction</u>. Providing a sufficiently large fetch is available, and providing the proper time averages (20 to 60 minutes) are used, the profiles of wind, temperature and humidity above an agricultural surface can be represented by the well-known logarithmic laws (e.g. Brutsaert, 1982; Rosenberg et al., 1983). By extrapolating the above-canopy

logarithmic profiles down into the canopy (where they in fact no longer hold) and integrating between the surface and the height of observation, one obtains the following expression for the bulk aerodynamic resistance (Thom and Oliver, 1977):

$$r_a = \frac{[\ln((z-d_m)/z_{om})-\psi_m]\ [\ln((z-d_s)/z_{os})-\psi_s]}{k^2\ u} \qquad (39)$$

where d_m = zero plane displacement for momentum transfer (m), d_s = zero plane displacement for scalar transfer (m), z_{om} = roughness length for momentum transfer (m), z_{os} = roughness length for scalar transfer (m), ψ_m = atmospheric stability correction for momentum, ψ_s = atmospheric stability correction for scalars and k = von Karman constant. The exact value of the von Karman constant is not known, but is generally accepted to be about 0.4 (Brutsaert, 1982).

The roughness length and zero plane displacement for momentum can be derived from measured wind profiles. This can be done graphically (e.g. Thom, 1975) or by means of simple analytical formulae (Monteith and Unsworth, 1990). A more involved approach based on a least squares technique was proposed by Lettau (1957). This method was implemented for computer solution by Robinson (1962) and Covey (1963). An expanded version capable of processing non-neutral profiles was developed by Stearns (1970).

The values of z_{om} and d_m are related to the height of the surface roughness elements, but also depend on the density and arrangement of the roughness elements and possibly on wind speed. For fully developed, dense crops z_{om} is about one tenth of the crop height and d_m about two thirds of the crop height. Empirical relationships for these conditions were derived from a large number of field measurements by Tanner and Pelton (1960) for z_{om} and Stanhill (1969) for d_m. Monteith (1973) simplified them into:

$$z_{om} = 0.13\ h \tag{40}$$

and

$$d_m = 0.63\ h \tag{41}$$

where h = crop height (m). By theoretical analysis, Kondo (1971) arrived at $z_{om}/h = 1/e^2$ for $d_m = 0$ and Brutsaert (1975a) obtained $z_{om}/h = 1/(3e)$ with $d_m = 2/3\ h$. Additional experimental observations for fully developed crops are given by Szeicz et al. (1969) for alfalfa and potatoes, by Thom (1971) for beans and by Munro and Oke (1973) for wheat.

For bare soils, z_{om} ranges from 1 mm to 1 cm (Oke, 1977) and d_m is usually assumed to be zero. Abtew et al. (1989) presented some theoretical relationships for z_{om} and d_m of bare soils based on clod size and clod exposure.

The magnitude of z_{om} and d_m for sparse canopies is not well quantified. An often cited experimental relationship is that of Lettau (1969), but this relation was developed for bluff bodies. Abtew et al. (1989) derived theoretical relationships, assuming a rigid plant structure. Numerical studies by Seginer (1973), Shaw and Pereira (1982) and Massman (1987a) showed that d_m can be expected to increase monotonically with density, whereas z_{om} probably is a unimodal function of density: at low densities, roughness increases with density, but beyond a certain threshold, a further increase in density causes a decrease in roughness. These numerical studies also indicated that z_{om} depends upon the vertical foliage distribution.

A special problem is that of row crops before row closure. Norman (as cited in Verma and Barfield, 1979) suggested to vary the ratios z_{om}/h and d_m/h for a partial corn canopy as a function of the ratio of crop height to row spacing. Similar suggestions were made by Azevedo and Verma (1986) for sorghum and Hatfield (1989) for cotton. Perrier et al. (1970, 1972) studied the flow above and within soybeans. They distinguished five types of flow occurring at different crop densities. The standard logarithmic law was shown to be applicable to very sparse or very dense canopies only. For intermediate densities, corrections were required to account for wake interference and for the formation of vortices in between rows. Arkin and Perrier (1974) more closely studied the behavior of these vortices by means of an artificial crop in a wind tunnel.

The variation of z_{om} and d_m with wind speed is still not fully understood and conflicting trends have been (and continue to be) reported. As a preliminary conclusion, one might state that some crops appear to become more streamlined with increasing wind speed and that, as a result, z_{om} and d_m tend to decrease with wind speed for these crops. Monteith (1973) provided a detailed discussion of the effects of wind speed, including an attempt to physically explain the observed variation of z_{om} and d_m for different types of agricultural crops.

Some recent experimental studies of the aerodynamic behavior of agricultural crops throughout their entire growing season that address some of the issues discussed above - but without reaching unanimous conclusions - were reported by Legg et al. (1981) for potatoes and beans, Azevedo and Verma (1986) for sorghum, Jacobs and Van Boxel (1988) for corn and Hatfield (1989) for cotton.

The hypothetical plane at the level $d_m + z_{om}$ acts as the virtual or effective momentum sink. Although this plane originated as a mathematical artefact, Thom (1971, 1975) was able to show that its location corresponds closely to the level of the mean drag on the surface elements.

The quantification of roughness length and zero plane displacement for scalars (heat and water vapor) is even more difficult than for momentum. Both parameters can be determined experimentally by analyzing measured profiles of temperature and humidity. For practical purposes, however, one usually tries to relate the profile parameters for scalar transport to those for momentum transport.

Since a partially bluff surface is more effective in exchanging momentum than it is for heat or water vapor, z_{om} is larger than z_{os}. Z_{os} can be linked to z_{om} as (Chamberlain, 1966):

$$z_{os} = z_{om} / \exp(kB^{-1}) \tag{42}$$

where B^{-1} = inverse surface sublayer Stanton number.

The parameter B^{-1} was first introduced by Owen and Thomson (1963). Chamberlain (1966) suggested a typical value of 5 for agricultural crops. Thom (1972) found that B^{-1} was around 4 for beans and varied with turbulence intensity. Garratt and Hicks (1973) compiled a variety of data for both bluff and permeable surfaces. They showed that B^{-1} depends on the type of surface (bluff or permeable) and on the roughness Reynolds number. Heilman and Kanemasu (1976) obtained values of B^{-1} around 2 for soybeans and sorghum. Brutsaert (1979) derived a theoretical formula for the ratio of z_{os} to z_{om} for tall, dense vegetation. Brutsaert (1982) suggested that for agricultural crops z_{os} can be estimated as one tenth of z_{om}.

The effect of canopy density on z_{os} was studied numerically by Kondo and Kawanaka (1986), Massman (1987b) and Massman and Van Dijken (1989). These studies indicate that z_{os} might also be a unimodal function of density.

Since a bare soil behaves as a bluff rather than as a permeable body, a different relation between z_{os} and z_{om} can be expected. Experimental relationships for rough and smooth bluff bodies were reviewed by Brutsaert (1975b) and Brutsaert (1982). The review by Garratt and Hicks (1973) indicated that for a freshly plowed soil B^{-1} ranges between 1 and 4.

Brutsaert (1982) suggested to assume that d_s is equal to d_m. This may not be the case, but from Eq. 39 it can be seen that the exact value of d_s or d_m is not very important whenever the height of measurement z is much larger than the crop height. The numerical study by Massman (1987b) showed that d_s, like d_m, increases monotonically with density.

The hypothetical level $d_s + z_{os}$ represents the virtual or effective source (or sink) for heat and water vapor. It is obvious, however, that the true locations of the sources and sinks for heat and water vapor must also be a function of soil moisture and are likely to assume different values for heat and water vapor, especially for partial canopies.

The stability functions ψ_m and ψ_s account for the fact that under stable conditions exchanges between the atmosphere and the surface are reduced, whereas under unstable conditions, they are enhanced by buoyancy forces. ψ_m and ψ_s are the integrated forms of the gradient stability corrections ϕ_m and ϕ_s. The latter are semi-empirical functions of the similarity parameters the Richardson number or the Monin-Obukhov length scale. Reviews of these functions were given by Dyer (1974), Yaglom (1977) and Brutsaert (1982). Their integration was discussed by Paulson (1970) and Benoit (1977). Brutsaert (1982) suggested that in the lowest 1 to 10 m of the atmosphere (a layer which he called the dynamic sublayer), mechanical turbulence is often more important than buoyancy, and stability effects can be ignored. Experimental studies by Bailey and Davies (1980), Allen (1986) and Van Zyl and De Jager (1987) confirmed that the inclusion of a stability correction in the aerodynamic resistance calculation did not improve the estimate of evapotranspiration by means of the Penman-Monteith equation. One should be aware of the fact that these results merely indicate that evapotranspiration was not very sensitive to aerodynamic resistance for the conditions investigated, and that they do not justify omitting stability corrections under all circumstances.

As indicated earlier, the validity of the logarithmic laws underlying Eq. 39 requires the use of 20 to 60 minute averages for the meteorological variables involved. In spite of these theoretical limitations, Grant (1975), Allen (1986) and Allen et al. (1989) obtained good results with daily average observations. Moreover, in engineering practice, daily averages are often the only ones available.

Surface Resistance

Definitions. This study uses the term "plant resistance" (r_{sc}) to indicate the resistance to transpiration exerted by the plants and "soil resistance" (r_{ss}) for the resistance to evaporation exerted by the drying soil surface. The resistance to evapotranspiration exerted by the surface as a whole is referred to as "surface resistance" (r_s). The term "canopy resistance" has been used by various authors to represent either plant resistance only or surface resistance as a whole and is therefore avoided.

Measurement. Surface resistance is usually back-calculated from various micrometeorological equations, including, but not limited to:

$$r_s = (\rho_a \, C_p/\gamma) \; (e^o(T_o) - e_o) \; / \; E \qquad (43)$$

and

$$r_s = r_a \; [(\Delta/\gamma)(H/E) - 1] + \rho_a \, C_p \; (e_s - e_a) \; / \; (\gamma E) \qquad (44)$$

Equation 43 was proposed by Monteith (1963) and requires knowledge of both temperature and humidity at the effective surface. Fuchs and Tanner (1967) warned that this equation should not be applied to bare soils. It namely assumes that the surface is isothermal, i.e. it assumes that the temperature of the vaporization site is the same as that of the effective source or sink of heat and water vapor. In the case of transpiration, it is not unreasonable to assume that the substomatal cavity has the same temperature as the canopy air space. In the case of evaporation, on the other hand, vaporization takes place somewhere in the wet subsoil and considerable temperature differences can exist between this site and the soil surface.

Equation 44, which was obtained by rewriting the Penman-Monteith equation with surface resistance as the unknown, only calls for measurements in the free atmosphere, but requires a knowledge of the aerodynamic resistance. Grant (1975) argued that since the Bowen ratio H/E often approximates the value γ/Δ, the multiplier of r_a approximates zero, rendering Eq. 44 insensitive to the exact value of r_a under certain conditions.

The plant resistance essentially represents a bulk stomatal resistance and can therefore also be estimated from measurements of individual leaf resistances (by means of a porometer) in combination with a measurement of leaf area index. Because leaf resistance varies with age and position in the canopy, an adequate sampling and averaging technique is required to obtain a representative value of plant resistance. Brun et al. (1973) discussed various methods for computing plant resistance from leaf resistance and leaf area index. Idso et al. (1988) warned that the use of a porometer is likely to alter the leaf microenvironment and may therefore lead to erroneous values for leaf resistance. When evaporation from the soil is negligible, plant resistance can also be measured directly by means of an evaporation chamber, which is placed over a section of the canopy. This technique was described by Kohsiek (1981). Since an evaporation chamber is basically a large porometer, it may cause problems similar to those described by Idso et al. (1988). No specific techniques for the separate measurement of soil resistance were found in the literature.

Numerous measurements of surface resistance have been published. Unfortunately, most of these reports only deal with hourly, daytime measurements, executed in the course of a few days only. Monteith et al. (1965) suggested that hourly values of surface resistance be converted into daily averages using net radiation as a weighing factor. Daily average surface resistances for agricultural crops throughout their growing season have been reported by Monteith et al. (1965) for barley, Grant (1975) for barley and Katerji and Perrier (1985) for alfalfa. These studies indicate that daily average surface resistance varies from 20 s m^{-1} for a fully developed, well-watered crop, to several hundred s m^{-1} for a developing or ripening crop.

Prediction. In spite of the large number of surface resistance determinations, very few practical relationships have been developed for predictive purposes. Under full cover conditions, plant resistance is usually estimated from leaf resistance and leaf area index, by assuming that all leaves act in parallel:

$$r_{sc} = r_{la} / LAI \qquad (45)$$

where r_{la} = average leaf resistance (s m^{-1}) and LAI = total leaf area index (m^2 m^{-2}).

The value of the leaf resistance in Eq. 45 should be representative of the average conditions in the entire canopy. It depends on radiation intensity, temperature, vapor pressure deficit and leaf water potential (itself related to soil moisture deficit). When a typical resistance for a sunlit leaf with open stomates is used, the total leaf area index should be replaced by the effective leaf area index, as proposed by Monteith et al. (1965):

$$r_{sc} = r_{ls} \;/\; LAI_{eff} \tag{46}$$

where r_{ls} = sunlit leaf resistance (s m^{-1}) and LAI_{eff} = effective leaf area index (m^2 m^{-2}).

Szeicz and Long (1969) suggested to estimate the effective leaf area index from:

$$LAI_{eff} = LAI \qquad \text{for} \quad LAI < LAI_{max}/2 \tag{47}$$

and

$$LAI_{eff} = LAI_{max}/2 \qquad \text{for} \quad LAI > LAI_{max}/2 \tag{48}$$

where LAI_{max} = maximum leaf area index for a fully developed crop (m^2 m^{-2}).

Because plant resistance is directly related to leaf resistance, it can be expected to depend on the same environmental factors. The effect of radiation can be addressed in several ways, with varying levels of sophistication. Allen (1986) proposed a simple empirical relation for plant resistance as a function of leaf area index and net radiation:

$$r_{sc} = (a_c - b_c\ R_n)/LAI \tag{49}$$

where a_c, b_c = empirical constants. Choudhury and Monteith (1988) combined a solar radiation penetration model with a model of leaf resistance as a function of solar radiation and obtained:

$$R_s(LAI) = R_s \exp(-K_{Rs}\ LAI) \tag{50a}$$

and

$$1/r_l = 1/r_{lc} + c_c\ R_s \tag{50b}$$

hence

$$1/r_{sc} = LAI/r_{lc} + c_c\ R_s\ [1-\exp(-K_{Rs}\ LAI)] \tag{50c}$$

where K_{Rs} = solar radiation extinction coefficient, r_l = leaf resistance (s m^{-1}), r_{lc} = leaf cuticular resistance (s m^{-1}) and c_c = constant reflecting stomatal response to solar radiation ($m^3\ J^{-1}$).

The effects of temperature and vapor pressure deficit on plant resistance are much more difficult to account for because leaves respond to the values of these parameters inside the canopy, which can be quite different from the atmospheric values. Contrary to the solar radiation profile, the within-canopy profiles of temperature and vapor pressure do not have a well defined shape and cannot easily be predicted from above-canopy measurements.

The effects of soil moisture deficit on surface resistance have been studied by Van Bavel (1967), Szeicz and Long (1969) and Russell (1980). These studies indicate that plant resistance remains fairly constant below a threshold value of soil moisture deficit. Once this threshold is exceeded, plant resistance increases rapidly. Models to predict the effect of soil moisture deficit on plant resistance have been proposed or tested by Grant (1975), Thompson et al. (1981) and Sherratt and Wheater (1984).

A special problem is that of a wet or partially wet canopy. In a wet canopy, transpiration is combined with evaporation of intercepted water. One commonly assumes that there is no resistance to evaporation from a free water surface. Shuttleworth (1975) showed theoretically that even a free water surface has an intrinsic surface resistance, but this resistance is negligibly small (< 0.1 s m^{-1}). The resistance of a partially wet canopy was studied theoretically by Shuttleworth (1976a) and Monteith (1977). Although the effects of wet or partially wet canopies can be very important in the case of forests, which can intercept appreciable amounts of water, they are of less importance when dealing with agricultural crops.

Various empirical models have been proposed for the estimation of soil resistance of bare soils. Grant (1975) suggested to vary soil resistance as a linear function of the number of days since the last wetting of 2 mm or more:

$$r_{ss} = 100\ [1+0.5\ t_w] \tag{51}$$

Shu Fen Sun (1982) and Camillo and Gurney (1986) proposed soil-specific models that relate soil resistance to the volumetric moisture content of the top 5 mm of the soil. They are of the form:

$$r_{ss} = a_s\ (\Theta_{sat}/\Theta)^{Cs} + b_s \tag{52}$$

and

$$r_{ss} = a_s\ (\Theta_{sat}-\Theta) + b_s \tag{53}$$

where a_s, b_s, c_s = soil specific empirical constants, Θ = volumetric soil moisture content ($m^3\ m^{-3}$) and Θ_{sat} = saturated soil moisture content ($m^3\ m^{-3}$). Choudhury and Monteith (1988) proposed to represent the soil as consisting of a dry surface layer overlying a wet subsoil. Water is assumed to vaporize at the interface between both layers and moves to the surface by molecular diffusion through the pores of the dry layer. The diffusion resistance is then given by:

$$r_{ss} = (t\ l)/(p\ D_w) \tag{54}$$

where t = tortuosity factor, l = thickness of the dry top layer (m), p = porosity ($m^3\ m^{-3}$) and D_w = diffusivity of water vapor ($m^2\ s^{-1}$). As evaporation progresses, the thickness of the dry layer increases and soil resistance increases. The models for soil resistance proposed in the literature predict a wide variety of resistance values. They range from 0 to 100 s m^{-1} for a wet soil and from less than 1000 up to 10,000 s m^{-1} for a dry soil.

For partial canopies, total surface resistance can be estimated by placing plant resistance and soil resistance in parallel. Jordan and Ritchie (1971) proposed:

$$1/r_s = f_c/r_{sc} + (1-f_c)/r_{ss} \tag{55}$$

where f_c = fraction cover. Grant (1975) used a radiation distribution function and obtained:

$$1/r_s = (1-K_R^{LAI})/r_{sc} + K_R^{LAI}/r_{ss} \tag{56}$$

where K_R = radiation extinction coefficient. In Eq. 55, r_{sc} represents the actual plant resistance of the crop under study (r_{ls}/LAI_{eff}), but in Eq. 56, r_{sc} should be given a minimum value representative of a fully developed crop ($r_{ls}/(LAI_{max}/2)$), irrespective of the actual growth stage. A review of the studies cited earlier in this section indicates that this minimum value lies between 20 and 40 s m^{-1}.

The Shuttleworth-Wallace Model

General Approach

Because of its single-layer nature, the extended Penman-Monteith model, described in the previous section, fails to account for the effects of the different elevations of the evaporation and transpiration sites within a partial canopy. Shuttleworth and Wallace (1985) recognized this shortcoming and, on the basis of the original Penman-Monteith equation, they developed a more detailed two-layer resistance model, specifically intended for use with partial canopies. The electrical analogue upon which the Shuttleworth-Wallace model is based, is shown in Fig. 2.

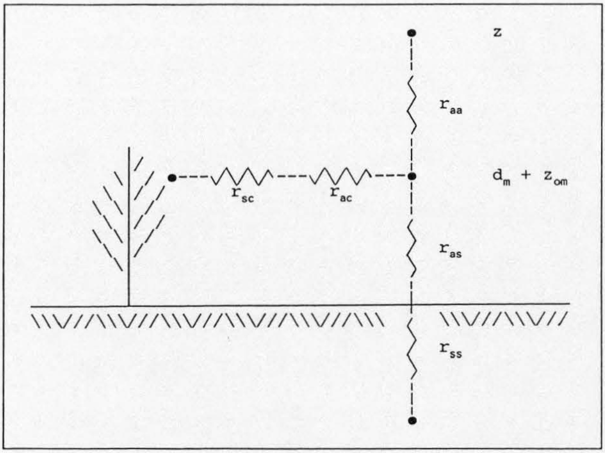

FIGURE 2. Two-Layer Electrical Analogue of the Evapotranspiration Process (after Shuttleworth and Wallace, 1985).

Figure 2 shows that the two-layer model contains five basic resistances, as compared to only three for the single-layer model. They are: the aerodynamic resistance (r_{aa}), the plant resistance (r_{sc}), the soil resistance (r_{ss}), the bulk leaf boundary layer resistance (r_{ac}) and the within-canopy transfer resistance (r_{as}). Plant resistance and bulk boundary layer resistance act in series and restrict the transfer of transpired water from the substomatal cavities into the mean canopy air stream. Soil resistance and within-canopy transfer resistance also act in series, but affect the flow of evaporated water from the wet subsoil into the mean canopy air stream. The mean canopy air conditions are assumed to exist at a height of $d_m + z_{om}$. The aerodynamic resistance controls the exchange between this canopy air space and the overlying atmosphere.

Once again, the discussion of the model will be limited to the final solutions and the reader is referred to the original presentation (Shuttleworth and Wallace, 1985) for a complete derivation. The final form of the Shuttleworth-Wallace model reads:

$$ET_c = C_c\ PM_c + C_s\ PM_s \qquad (57)$$

where C_c, C_s = coefficients, PM_c = Penman-Monteith sub-model for a closed canopy (W m^{-2}), PM_s = Penman-Monteith sub-model for a bare soil (W m^{-2}).

The sub-models for the closed canopy and bare soil are similar in form to the Penman-Monteith equation:

$$PM_c = \frac{\Delta(R_n-G)+[\rho C_p(e_s-e_a)-\Delta r_{ac}(R_{ns}-G)]/(r_{aa}+r_{ac})}{\Delta + \gamma\ [1 + r_{sc}/(r_{aa}+r_{ac})]} \qquad (58)$$

and

$$PM_s = \frac{\Delta(R_n-G)+[\rho C_p(e_s-e_a)-\Delta r_{as}(R_n-R_{ns})]/(r_{aa}+r_{as})}{\Delta + \gamma\ [1 + r_{ss}/(r_{aa}+r_{as})]} \tag{59}$$

where R_n = net radiation measured above a sparse crop (W m^{-2}) and R_{ns} = net radiation received at the soil surface (W m^{-2}). The coefficients C_c and C_s are given by:

$$C_c = \{1 + R_c\ R_a\ /\ [R_s\ (R_c + R_a)]\}^{-1} \tag{60}$$

and

$$C_s = \{1 + R_s\ R_a\ /\ [R_c\ (R_s + R_a)]\}^{-1} \tag{61}$$

where R_a, R_s and R_c are defined as:

$$R_a = (\Delta + \gamma)\ r_{aa} \tag{62}$$

$$R_s = (\Delta + \gamma)\ r_{as} + \gamma\ r_{ss} \tag{63}$$

$$R_c = (\Delta + \gamma)\ r_{ac} + \gamma\ r_{sc} \tag{64}$$

The net radiation received at the surface can be obtained from:

$$R_{ns} = R_n\ \exp(-K_{Rn}\ LAI) \tag{65}$$

where K_{Rn} = net radiation extinction coefficient.

Following the same approach as for the Penman-Monteith model, each of the various resistance terms in the Shuttleworth-Wallace model will now be discussed in greater detail.

Aerodynamic Resistance

The expression for aerodynamic resistance in the two-layer model is based on the assumption that for a dense crop, the eddy diffusivities above the canopy can be obtained from the logarithmic wind profile, whereas the eddy diffusivities within the canopy are assumed to decrease exponentially with depth measured from the top of the canopy. For a bare soil, on the other hand, the logarithmic wind profile is assumed to extend all the way down to the soil surface.

If a given crop is dense enough for the wind profile to behave like the profile above a dense crop, integrating the exponential profile between the mean canopy airstream and the canopy height and subsequently integrating the logarithmic profile between the canopy height and the reference height, neglecting stability effects, yields (Shuttleworth and Wallace, 1985):

$$r_{aa}(DC) = \{\ln[(z-d_m)/z_{om}]/(k^2u)\} \{\ln[(z-d_m)/(h-d_m)] + h/[K_K(h-d_m)] [\exp(K_K[1-(d_m+z_{om})/h]) - 1]\} \tag{66}$$

where K_K = eddy diffusivity attenuation coefficient and DC stands for dense crop.

If, on the other hand, a given crop is sparse enough for the wind profile to behave like the one above a bare soil, integration of the logarithmic profile between the mean canopy airstream and the reference height yields (Shuttleworth and Wallace, 1985):

$$r_{aa}(BS) = \ln[z/z_{om}']/(k^2u) \ln[z/(d_m+z_{om})] \qquad (67)$$

where z_{om}' = roughness length of a bare soil (m) and BS stands for bare soil.

For a moderately dense crop, the true aerodynamic resistance is expected to lie between the extremes specified by Eqs. 66 and 67. Crops with a leaf area index higher than a threshold value are assumed to behave like a dense crop. For crops with a lower leaf area index, aerodynamic resistance is estimated by linearly interpolating between both extremes. In summary (Shuttleworth and Wallace, 1985):

$$r_{aa} = r_{aa}(DC) \qquad \text{for } LAI>LAI_{dc} \qquad (68)$$

and

$$r_{aa} = [LAIr_{aa}(DC)+(LAI_{dc}-LAI)r_{aa}(BS)]/LAI_{dc} \qquad (69)$$

otherwise, where LAI_{dc} = threshold value of leaf area index required for a crop to be considered dense ($m^2\ m^{-2}$).

Plant Resistance

Plant resistance can be estimated in the same way as for a single-layer model, namely by dividing a representative individual leaf resistance by the effective leaf area index, as shown previously in Eqs. 46 through 48.

Soil Resistance

Soil resistance too, does not differ from the soil resistance in a single-layer model. It can be estimated by procedures such as those given in Eqs. 51 through 54.

Boundary Layer Resistance

Just like plant resistance represents the effect of all individual leaf resistances in parallel, the bulk boundary layer resistance represents the effect of all individual leaf boundary layers in parallel. It can therefore be estimated from:

$$r_{ac} = r_b \, / \, LAI_{eff} \tag{70}$$

where r_b =individual leaf boundary layer resistance (s m^{-1}).

Strictly speaking, the bulk boundary layer resistance should also include a transfer component describing the resistance to vapor transfer from the canopy air surrounding a given leaf into the mean canopy airstream, but this effect is not explicitly accounted for.

The individual leaf boundary layer resistance depends on the thickness of the laminar boundary layer surrounding the leaf. The thickness of this layer is itself a function of leaf size and within-canopy wind speed. Leaf boundary layers are usually described by means of a series of non-dimensional numbers from fluid mechanics. A detailed treatment of this subject can be found in Gates (1980) and Monteith and Unsworth (1990).

Choudhury and Monteith (1988) combined an exponential canopy wind profile with a simple model for leaf boundary layer resistance as a function of wind speed (Jones, 1983) and obtained:

$$u(z) = u(h)\ \exp[K_u(z/h-1)] \tag{71a}$$

and

$$1/r_b = a_b\ (u(z)/w_l)^{1/2} \tag{71b}$$

hence

$$1/r_{ac} = LAI(2a_b/K_u)(u(h)/w_l)^{1/2}[1-\exp(-K_u/2)] \tag{71c}$$

where K_u = wind speed attenuation coefficient, w_l = leaf width (m) and a_b = constant equal to 0.01 m $s^{-1/2}$.

Transfer Resistance

The estimation of the within-canopy transfer resistance follows the same pattern used for aerodynamic resistance. For a dense crop in which an exponential diffusivity profile exists, integration of this exponential profile between the surface and the mean canopy airstream gives (Shuttleworth and Wallace, 1985):

$$r_{as}(DC) = \{\ln[(z-d_m)/z_{om}]/(k^2u)\}\ \{h/[K_K(h-d_m)]\}$$
$$\{\exp(K_K) - \exp(K_K[1-(d_m+z_{om})/h])\} \tag{72}$$

For a very sparse crop in which a logarithmic wind profile exists, integration of the logarithmic profile between the same levels yields (Shuttleworth and Wallace, 1985):

$$r_{as}(BS) = \ln[z/z_{om}'] \ln[(d_m+z_{om})/z_{om}']/(k^2u) \qquad (73)$$

For crops with an intermediate density, transfer resistance is obtained by linear interpolation (Shuttleworth and Wallace, 1985):

$$r_{as} = r_{as}(DC) \qquad \text{for} \quad LAI>LAI_{dc} \qquad (74)$$

and

$$r_{as} = [LAI r_{as}(FC)+(LAI_{dc}-LAI) r_{as}(BS)]/LAI_{dc} \qquad (75)$$

otherwise.

CHAPTER IV

PROCEDURES

Site Description[1]

General

All data used in this study were obtained at or near the USDA-ARS Soil and Water Management Research Center at Kimberly, Idaho. The research center is located at 42°33' North latitude, 114°21' West longitude at an elevation of about 1200 m. It lies in the interior of a large (263,000 ha) irrigated area. The region is reasonably flat (variations in elevation are less than 100 m) and is bordered by a low mountain range in the South, a higher mountain range and rangeland in the North and non irrigated sagebrush-grass rangeland in the West.

The local climate is arid. The average frost-free period is about 120 days, extending from mid-May to mid-September. Most of the annual precipitation falls outside the growing season. The average total precipitation for the entire growing season amounts to about 100 mm only. The prevailing winds come from the West and carry hot and dry desert air into the area, subjecting it to considerable regional advection (studied in detail by Burman et al., 1975).

---

[1] Data taken from Burman et al.(1975) and Wright (1982,1988)

USDA-ARS Lysimeter Site

Most of the data used in this study were collected at the USDA-ARS lysimeter site, located about 800 m South of the USDA-ARS research center. The lysimeter site consists of two fields (2.6 and 2.2 ha in size), each equipped with a weighing lysimeter and micrometeorological instrumentation. At the time of the measurements, the East field also housed a meteorological tower. In this study, only data from the East lysimeter field were used. The East lysimeter and its accompanying instrumentation are located in the center of the 2.6 ha lysimeter field, providing a uniform fetch of about 100 m in the prevailing wind direction.

The soil at the lysimeter site is a Portneuf silt loam, 4 m deep and underlain by basalt bedrock. Wright (1988) added that at a depth of 0.5 to 1 m, there is a hard layer consisting of rounded nodules of very hard soil material, partly restrictive to root penetration, but permeable to water flow. The soil is well drained, has no water table and is well suited for irrigation (Wright, 1988).

U.S. Weather Service Station

This study also made use of some measurements executed at the U.S. Weather Service station located adjacent to the USDA-ARS research center. The site consists of a clipped grass plot, 45 m x 36 m in size, equipped with standard meteorological equipment. The station is bordered by a building about 50 m to the North, an asphalt road about 50 m to the East, agricultural experiment plots immediately to the South and trees and houses about 250 m to the West.

Data Collection

Original Observations

All measurements at the USDA-ARS lysimeter site were carried out during the period 1973-1974 and 1978-1979 by Dr. J.L. Wright, soil scientist with USDA-ARS, Kimberly. Measurements at the U.S. Weather Service station were executed during the same period by U.S. Weather Service staff. The data from the lysimeter site were made available for this study by Dr. J.L. Wright (1988-1990, personal communication).

Crop evapotranspiration was measured by means of a sensitive weighing lysimeter with a surface area of 1.83 m x 1.83 m and a depth of 1.22 m. More detailed descriptions of the lysimeter and its operation are given by Wright (1982) and Wright (1988).

Besides evapotranspiration, a number of other meteorological variables were measured. Meteorological measurements near the lysimeter included (but were not limited to) air temperature, dew point, wind speed, wind direction, soil temperature, soil heat flux, solar radiation and net radiation. Air temperature was measured by means of a Copper-Constantan thermocouple connected to an ice-point reference. Dew points were determined by means of a lithium chloride dew probe. The thermocouple and dew probe were housed in a single aspirated unit, mounted at 2 m. Wind speed was measured by means of a Gill 3 cup rotating cup anemometer, equipped with a photo-diode light chopper, also installed at 2 m. Wind direction was measured by means of a Gill Microvane wind vane mounted at 2 m. Soil heat flux was measured by means of two Micromet soil heat flux plates, buried at 5 cm depth inside and outside the lysimeter. Likewise, soil temperatures were recorded by two sets of Copper-Constantan thermocouples installed at various depths inside and outside the lysimeter (the exact locations depended on the year of study). Solar radiation was measured with an Eppley pyranometer and net radiation by means of an aspirated FRINET Miniature Net Radiometer.

A meteorological tower provided additional measurements of air temperature and dew point at 1 m, 2 m, 3 m, 5 m, 8 m, 11 m and 14 m. Additional wind speeds were measured at 2 m, 3 m, 5 m, 8 m, 11 m and 14 m. A second wind vane, installed at the top of the tower, provided a measurement of wind direction at 14 m.

All measurements listed above were recorded at 20 or 60 minute intervals by an automatic data acquisition system. After retrieval, all 20 minute readings were combined into hourly averages. Occasionally, the data recorder malfunctioned, resulting in missing data sequences for up to several consecutive days.

The electronic measurements of meteorological variables were complemented by manual observations of plant and soil parameters, performed at regular time intervals. These measurements included crop height, leaf area index, dry matter accumulation, soil moisture content and soil moisture tension.

Finally, extensive records were kept, detailing cultural practices and plant phenology as well as field, weather and instrument conditions. These records include a large collection of slides, illustrating crop development on the lysimeter and in the surrounding field.

Table 2 lists the various crops grown on the East lysimeter during the period of study. Table 3 lists their key growth stages.

TABLE 2. Selected Crops Studied at the USDA-ARS Lysimeter Site.

Year	Crop
1973	Snap beans (Phaseolus vulgaris, L.)
1974	Snap beans (Phaseolus vulgaris, L.)
1978	Winter wheat (Triticum aestivum, L.)
1979	Spring wheat (Triticum aestivum, L.)

TABLE 3. Key Growth Stages of Selected Lysimeter Crops.

Crop	Planting	Emergence	Eff.Cover	Ripening	Harvest
Snap beans 1	5/22	5/31	7/15	8/15	8/27
Snap beans 2	5/23	5/31	7/15	8/15	8/28
Winter wheat	10/10	10/25	6/05	7/15	8/14
Spring wheat	4/11	4/23	6/20	7/30	8/20

All crops were furrow irrigated and cultural practices were modelled after those common to the area.

The observations at the U.S. Weather Service station included daily minimum and maximum temperature (from minimum and maximum thermometers installed in a meteorological shelter at 1.35 m), dewpoint at 8 am (from measured wet and dry bulb temperatures, also at 1.35 m), daily wind travel (from a rotating cup anemometer installed at 3.66 m), daily solar radiation (from an Eppley pyranometer installed on the roof of the USDA-ARS research center) and pan evaporation (from a U.S. Class A evaporation pan). Most measurements were recorded manually and records are almost continuous.

Additional Observations

During the Summer of 1989, a number of additional measurements were executed on a field of spring wheat (Triticum aestivum, L.) about 200 m northwest of the lysimeter site and on two snap bean (Phaseolus vulgaris, L.) fields immediately south of the lysimeter site.

The observations consisted of air temperature (measured by 0.076 mm Omega Constantan-Chromel thermocouples at 1 m and 2 m), relative humidity (from Hygrometrix Xeritron humidity sensors at 1 m and 2 m), surface temperature (observed with an Everest Interscience model 4000 infrared thermometer), wind speed (measured by means of R.M. Young Gill 3 cup anemometers with photo-diode light choppers installed at 0.5, 1.0, 1.5 and 2.0 m), wind direction (obtained from an R.M. Young Gill Microvane placed at about 3 m) and eddy correlation measurements of sensible heat flux (by means of a Campbell Scientific CA27 sonic anemometer including a fine wire thermocouple suspended at 1.5 m).

All data were recorded by means of a Campbell Scientific 21X micrologger and stored onto cassette tape. The sonic anemometer was sampled at 10 Hz. Covariances were automatically computed at the end of each 10 minute measurement period and then converted to 30 minute averages. Whenever there was a threat of rain, the measurement of sensible heat flux had to be discontinued because of the possibility of water damage to the sonic anemometer. All other sensors were operated continuously. They were sampled every 30 seconds, but only 10 minute averages were stored.

In addition, manual observations of plant height and row width (beans only) were made at weekly intervals. Cultural practices, weather and soil surface conditions were recorded.

The measurements on the spring wheat field took place from June 19 through July 1. This period coincided with the formation of grain heads and the wheat grew from 50 cm at the beginning of the observations to 70 cm at the end. The instruments were set up near the East side of the field, leaving a uniform fetch of more than 100 m in the prevailing wind direction.

The measurements on the snap bean fields were made from July 1 through September 3. This period spanned the entire growing cycle from shortly after emergence (plants 10-15 cm high) until harvest. During the period of observation, both bean crops reached maximum heights of 45 cm. One field had rows running North-South, whereas the other one had East-West rows. Twice, the instruments were moved from one field to the other. At all times, the instruments were set up in the center of the fields, providing a uniform fetch of at least 100 m in all directions.

Prior to the execution of the measurements, most of the sensors were checked and calibrated. The two Constantan-Chromel thermocouples were compared to each other by suspending them immediately next to each other. In general, differences of less than 0.05 °C were observed. The differences between both sensors exhibited a clear daily cycle, which may have been the result of differences in irradiation of the suspension arms. When both thermocouples were taken indoors and were dipped into stirred water, the differences were reduced to 0.02 °C or less.

The factory calibration of the infrared thermometer was checked by means of an Everest temperature reference target. Target temperatures were measured by means of the infrared thermometer, after making a software correction to account for the target emissivity (0.99). The radiative temperatures obtained by means of the infrared thermometer were within

0.2 °C of those measured by the built-in thermopile of the reference target over the temperature range 10 °C to 45 °C.

The relative humidity sensors were compared to each other by suspending them above various salt solutions. The readings of both sensors were within 2 % of each other, over the humidity range 10 % to 85 %. The absolute values, however, were up to 15 % different from those expected for the salt solutions under consideration. This difference may have been caused by errors in the preparation of the salt solutions.

The wind speed measurements on the spring wheat field were executed with a set of four anemometers, two of which were used and two of which were new. These anemometers were compared to each other by mounting them on a saw horse at about 0.5 m height and spaced about 1 m apart. A two day calibration run showed that the old and the new anemometers agreed very well with each other, but, in general, the old anemometers gave slightly higher readings than the new ones. Both sets were matched by slightly reducing the slope of the calibration curve of the old anemometers and slightly increasing the slope of the calibration curve for the new anemometers. After this matching procedure, differences between the four anemometers were reduced to 3 % in the long run (two day average) with occasional short term differences of up to 15 %. High short term differences occurred at both high and low wind speeds and may have been related to wind direction (one anemometer shielding the other). After completing the measurements on the spring wheat field, the two old anemometers were replaced by new ones. As a result, all measurements on the snap bean fields could be executed by means of four new anemometers of the same type. After completion of all measurements, the four new anemometers were compared to each other. A seven day calibration run indicated that the long term difference between all anemometers was less than 2.5 %. Short term differences, on the other hand, clearly increased with decreasing wind speed, reaching 20 % or more for wind speeds less than 0.5 $m\ s^{-1}$.

Determination of Resistances

Aerodynamic Resistance

The evaluation of aerodynamic resistance was performed on the basis of the additional measurements executed during the Summer of 1989, described in the previous section.

Wind Profile Parameters. Prior to the analysis, all 10 minute average wind speed measurements were grouped into 30 minute averages. The resulting mean half hourly wind profiles were visually inspected.

While executing the measurements on the spring wheat field, it was noted that the lowest anemometer often malfunctioned (no pulse registration), especially under conditions of high humidity, i.e. at night and in the early morning. By the end of the observation period, this anemometer was also located inside the wheat canopy, rather than above it. For these two reasons, the readings from the lowest anemometer were discarded. Since the tower was located on the eastern edge of the spring wheat field, only data obtained with a wind direction ranging from North-West to South-West were analyzed.

When the measurements on the snap bean fields began, the two lower anemometers were replaced by new ones, which appeared to function satisfactorily. Because the instruments were located in the center of the fields, profiles obtained with all possible wind directions were inspected. This inspection revealed that whenever winds blew from the East, the recorded wind profiles were distorted. Since the anemometers were attached to the West side of the instrument tower, these distortions were probably the result of interference caused by other instruments, especially the voluminous data logger case. As a result of these observations, all wind profiles obtained with wind directions ranging from North East to South East were excluded from the analysis. By the middle of the growing season, the beans had grown to 45 cm height and the lowest anemometer was located only 5 cm above the surface. As a result, it may have been positioned inside the roughness sublayer, where the logarithmic laws are no longer applicable. Therefore, readings from the lowest anemometer were, once again, excluded from the analysis.

The values of roughness length and zero plane displacement should be computed from wind profiles measured under neutral atmospheric conditions only (Thom, 1975; Monteith and Unsworth, 1990). For each half hour period, neutrality was investigated by means of the following three discrete approximations of the gradient Richardson number:

$$Ri_1 = \frac{2\ g\ (T_1 - T_0)\ (1 - d_{est})}{(T_0 + T_1)\ u_1^2} \tag{76}$$

$$Ri_2 = \frac{2\ g\ (T_2 - T_0)\ (2 - d_{est})}{(T_0 + T_2)\ u_2^2} \tag{77}$$

$$Ri_3 = \frac{2\ g\ (T_2 - T_1)}{(T_1 + T_2)\ (u_2 - u_1)^2} \tag{78}$$

where Ri_1, Ri_2 and Ri_3 = various discrete approximations of the gradient Richardson number; T_0, T_1 and T_2 = temperatures at the surface, 1 m and 2 m respectively (K); u_1, u_2 = horizontal wind speed at 1 m and 2 m (m s^{-1}) and d_{est} = estimated zero plane displacement (m).

Strictly speaking, Richardson numbers should be computed from virtual potential temperatures instead of measured temperatures (Brutsaert, 1982; Rosenberg et al., 1983). In this study, however, all measurements were made closely together (less than 2 m apart), so the use of measured temperatures instead of potential temperatures does not result in errors of more than a few hundreds of a degree Celsius. Relative humidities were measured at 1 m and 2 m, but an inspection of the data showed that the measured gradients (often only a few percent) were usually less than the instrument error (4 % according to the manufacturer). As a result, the effect of using measured temperatures, rather than virtual temperatures in Eq. 78 should be limited. There were no measurements of surface humidity, but it is likely that considerable humidity gradients existed between the surface and the air at 1 or 2 m. Therefore, Eqs. 76 and 77 are less reliable than Eq. 78. Furthermore, the instrument to measure surface temperature was different from those used to measure air temperature. As a result, the temperature gradient in Eq. 78 is more accurate than those in Eqs. 76 and 77. Finally, the use of Eqs. 76 and 77 requires a preliminary estimate of zero plane displacement, which introduces additional uncertainty. A comparison showed that Ri_3 was usually larger than Ri_1 or Ri_2. In other words, Eq. 78 poses a stricter criterion for neutrality than Eqs. 76 and 77. Therefore, neutral conditions were distinguished on the basis of:

$$-0.01 < Ri_3 < 0.01 \tag{79}$$

Roughness length and zero plane displacement were obtained from neutral profiles by means of two simplified techniques. The first technique was based on an iterative log-linear regression and was basically an analytical version of the graphical techniques described by Monteith (1973), Thom (1975) and Monteith and Unsworth (1990). When d_m has the correct value, $\ln(z-d_m)$ is linearly related to wind speed:

$$\ln(z-d_m) = \ln(z_{om}) + (k/u_*)\ u \qquad (80)$$

or

$$\ln(z-d_m) = i + s\ u \qquad (81)$$

where z = measurement height (m), u = wind speed (m s^{-1}), i = intercept, s = slope (s m^{-1}) and u_* = friction velocity (m s^{-1}). The optimal value of d_m was determined by iteration: all values of d_m ranging from 0 to h with an increment of 0.01 h were tested. For each value of d_m, the linearity of the relation between $\ln(z-d_m)$ and u was evaluated by means of the correlation coefficient. The value of d_m which yielded the highest correlation was retained. Once d_m was known, z_{om} was obtained as the exponent of the intercept. The approach was tested by analyzing a number of artificial profiles, generated with chosen values of z_{om} and d_m. The analysis invariably returned the original values of z_{om} and d_m.

The second technique involved the use of the relationships given by Monteith and Unsworth (1990). When three measurements of wind speed are available, zero plane displacement can be obtained from:

$$\frac{(u_a - u_b)}{(u_a - u_c)} = \frac{\ln(z_a - d_m) - \ln(z_b - d_m)}{\ln(z_a - d_m) - \ln(z_c - d_m)} \tag{82}$$

where u_a, u_b and u_c = wind speed at levels a, b and c (m s^{-1}) and z_a, z_b and z_c = elevation of levels a, b and c (m).

If zero plane displacement is known, roughness length can be obtained from two measurements of wind speed as:

$$z_{om} = \exp\left[\frac{u_b \ln(z_a - d_m) - u_a \ln(z_b - d_m)}{u_b - u_a}\right] \tag{83}$$

Equation 82 is implicit and was solved iteratively by means of the Newton-Secant method. Subsequently, three different values of z_{om} were computed from Eq. 83 through various combinations of the available observations, namely z_{om1} (from observations at 1.0 and 1.5 m), z_{om2} (from observations at 1.5 and 2.0 m) and z_{om3} (from observations at 1.0 and 2.0 m).

Aerodynamic Resistance. "Measured" values of aerodynamic resistances were obtained from:

$$r_{a1} = (T_0 - T_1) / \overline{w'T'} \tag{84}$$

$$r_{a2} = (T_0 - T_2) / \overline{w'T'} \tag{85}$$

$$r_{a3} = (T_1 - T_2) / \overline{w'T'} \tag{86}$$

where all temperatures and covariances were measured directly using the infrared radiometer, fine wire thermocouples and sonic anemometer. These "measured" values of aerodynamic resistance were compared to computed values, not corrected for stability, calculated from:

$$r_{a1}' = \frac{\ln((z_1-d_m)/z_{om})\ \ln((z_1-d_h)/z_{os})}{k^2\ u_1} \tag{87}$$

$$r_{a2}' = \frac{\ln((z_2-d_m)/z_{om})\ \ln((z_2-d_h)/z_{os})}{k^2\ u_2} \tag{88}$$

$$r_{a3}' = \frac{\ln((z_2-d_m)/(z_1-d_m))\ \ln((z_2-d_h)/(z_1-d_h))}{k^2\ (u_2-u_1)} \tag{89}$$

The goal of this comparison was to evaluate the performance of Eqs. 87 through 89 and to determine the need for a stability correction to these equations. All the resistance computations listed above were performed on hourly average data.

Surface Resistance

The evaluation of surface resistance was carried out by means of the lysimeter measurements made by Dr. J.L. Wright during 1973-1974 (beans) and 1978-1979 (wheat). In addition, the soil resistance of a bare soil was evaluated by means of lysimeter measurements from 1977.

Preliminary Work. Prior to use, the electronically retrieved lysimeter and associated weather data were subjected to considerable manual adjustments. In a first stage, field notes and chart recordings of lysimeter mass were used to adjust electronically recorded changes in lysimeter mass affected by irrigation, precipitation and a number of exceptional events (e.g. installing or removing tensiometers, removal of excess water...). Evapotranspiration during irrigations was estimated by extrapolating the changes in lysimeter mass just before and just after the irrigation. Evapotranspiration during rainfall, on the other hand, was assumed to be zero.

After these first corrections, a subset of measured variables was plotted and visually inspected. The variables checked were net radiation, solar radiation, soil heat flux, lysimeter evapotranspiration, air temperature at 2 m, vapor pressure at 2 m and wind speed at 2 m. A number of measurements from the meteorological tower were also inspected, namely temperature and vapor pressure at 1 m, 2 m and 3 m and wind speed at 2 m and 3 m. Whenever erroneous values of a variable were observed for one or a few hours, they were corrected manually. When readings were in error for more than a few hours, the entire day was rejected. Days with incomplete data sequences were also removed from the data set. Inspection revealed that the measured hourly values of lysimeter evapotranspiration contained a significant amount of noise, probably induced by wind speed fluctuations, especially during the beginning of the growing season. The inspection also showed that the wind speed gradient between 2 and 3 m was unreliable at low wind speeds throughout the 1973 and 1974 growing seasons. Obvious erroneous readings were tentatively corrected, but many problem values remained.

Values of solar radiation were checked by comparing them to the clear sky solar radiation, estimated as three fourths of the extra-terrestrial radiation (see Eq. 19). The solar radiation readings for 1978 and 1979 fell on or below the clear sky envelope, but readings from 1973 and 1974 appeared to be too high on occasion. Therefore, daily solar radiation measurements for 1973 and 1974 were replaced by more accurate values, published by Wright (1978).

In addition, the measurements of solar radiation, temperature, vapor pressure and wind speed were checked by plotting the observations at the lysimeter site against those obtained the U.S. Weather Service station. Although these data cannot be expected to be identical, general trends should be similar and sharp discrepancies between both data sets were indicative of a problem in either set.

Daily estimates of crop height and leaf area index were obtained by manually drawing smooth curves through the intermittent measurements. Several problems were encountered in this process.

The first problem resulted from non-representative lysimeter conditions. During some of the years of study, growth conditions on the lysimeter differed quite a bit from those in the surrounding field. Crop heights were measured on the lysimeter and in the field, but leaf area index was measured in the field only. Since aerodynamic resistance is mainly determined by the aerodynamic roughness of the upwind fetch, measurements of crop heights in the field were used rather than those on the lysimeter. Plant resistance, on the other hand, is determined by the leaf area index on the lysimeter only. Values of leaf area index on the lysimeter were estimated on the basis of measurements in the field complemented by field notes and archive slides.

Another problem involved the estimation of crop heights after lodging. Both in 1973 and 1974 the bean crops were reported to have lodged as a result of wind action. Up to the day of lodging (around July 20 in 1973, around July 30 in 1974), reliable measurements of crop height were available. Crop heights after lodging were roughly estimated to be 40 cm for both years (on the basis of measurements in 1974) and are therefore unreliable.

The estimation of leaf area index towards harvest also posed a problem. In all four years of study, the measurement of leaf area index was discontinued around the beginning of ripening. Since both beans and wheat dry out towards harvest, the green leaf area index at harvest was rather arbitrarily assumed to be 0.5 for beans and 0.1 for wheat.

A smooth curve was drawn to connect the last measured value to the estimated value at harvest.

During some of the years of study, very specific problems occurred. In 1973, the beans on the lysimeter developed much faster than those in the field. After lodging, the beans on the lysimeter were affected by a severe mold problem, causing some of the plants to die prematurely. As a result, the leaf area index on the lysimeter decreased much faster than in the field. In an attempt to slow down the mold infection, the beans on the lysimeter were tied to stakes and strings were used to open up the rows and dry out the soil surface.

In 1978, lysimeter and field developed in a similar fashion, but towards the end of the season, the field ripened much faster than the lysimeter. In order to better approximate the ripening of the lysimeter, the very fast decrease of leaf area index during ripening was postponed and made to coincide with the rapid increase in albedo, measured at or near the lysimeter.

In 1979, the spring wheat germinated in two distinct phases. As a result, the field had a patchy appearance with high and low spots throughout the first half of the growing season. During this period, crop height and leaf area index were estimated by simply taking the average of the observed range in the measurements. As was done for the winter wheat, the rapid decline of leaf area index towards harvest was made to coincide with the observed increase in albedo.

In 1977, the lysimeter surface remained bare throughout August and September. During this period all instruments remained operational, the lysimeter and its surroundings were kept free from weeds, and several irrigations took place. Two data series of eight days, each representing an undisturbed drying sequence following an irrigation, were retrieved. The first series ran from August 10 through August 17 (following irrigation on August 9 at 5 pm) and the second one ran from September 2 through September 9 (following irrigation on September 1 at 7 pm). The second series was continuous and all data appeared to be in order. The first series contained two problems: as a result of recorder malfunction, there was an 16 hour discontinuity during the night from August 15 to August 16, and, due to instrument malfunction, net radiation values were too low throughout the entire sequence. The net radiation values were adjusted upwards in a crude but conservative manner and may be up to ten percent low. The missing data sequence was filled in by superposing the data on those from the previous and following nights and extrapolating the measured data surrounding the discontinuity.

Surface Resistance. Surface resistances throughout the growing season were obtained by back-calculation from:

$$r_s = [(\Delta/\gamma)(R_n-G-E)/E-1]r_a + \rho_a C_p(e_s-e_a)/(\gamma E) \qquad (90)$$

In Eq. 90, R_n, G and e_a were measured directly, E was obtained by multiplying the lysimeter evapotranspiration (in mm) by λ (with λ from Eq. 12) and Δ, γ, ρ_a and C_p were computed from Eqs. 9, 11, 32 and 14 respectively. e_s was computed from Eqs. 6 and 7 for hourly and daily computations respectively. Whenever needed, P was assumed to be 87.5 kPa (Wright, 1982).

Two versions of aerodynamic resistance were used: with and without stability correction. The uncorrected aerodynamic resistance was obtained from:

$$r_a' = \frac{\ln((2-d_m)/z_{om}))\ \ln((2-d_s)/z_{os})}{k^2\ u} \tag{91}$$

As a first approximation (in part supported by the measurements executed at Kimberly during the Summer of 1989, see results), it was assumed that:

$$z_{om} = 0.10\ h \tag{92}$$

$$d_m = 0.67\ h \tag{93}$$

$$z_{os} = 0.20\ z_{om} \tag{94}$$

$$d_s = d_m \tag{95}$$

The above equations predict that before emergence (when h equals 0) z_{om}, d_m, z_{os} and d_s are all zero. The zero plane displacement of a bare soil is most likely to be zero indeed, but its roughness length is not. Therefore, whenever the roughness length predicted by Eq. 92 was less than the apparent roughness length of bare soil (see later), it was replaced by this apparent roughness length.

The stability corrected aerodynamic resistance was roughly estimated as:

$$r_a'' = r_a' \, \Phi_m \, \Phi_s \tag{96}$$

where the functions Φ_m and Φ_s represent average values of the gradient stability functions ϕ_m and ϕ_s (which differ from the integrated values Ψ_m and Ψ_s in Eq. 39). They were evaluated from (Pruitt et al., 1973):

$$\Phi_m = (1+16\ Ri_{avg})^{1/3} \qquad \text{(stable)} \tag{97}$$

$$\Phi_m = (1-16\ Ri_{avg})^{-1/3} \qquad \text{(unstable)} \tag{98}$$

$$\Phi_s = 0.885\ (1+34\ Ri_{avg})^{2/5} \qquad \text{(stable)} \tag{99}$$

$$\Phi_s = 0.885\ (1-22\ Ri_{avg})^{-2/5} \qquad \text{(unstable)} \tag{100}$$

where Ri_{avg} = average Richardson number, representative of the stability in the air layer between the canopy and the reference height (2 m). The value of Ri_{avg} was estimated by two different procedures. The first procedure made use of measured profiles and required a two stage process. First, a Richardson number was computed from tower observations of temperature, wind speed and humidity at 2 m and 3 m (the lowest two levels for which all these variables were available):

$$Ri_m = \frac{2\ g\ (T_{v3} - T_{v2})}{(T_{v2} + T_{v3})\ (u_3 - u_2)^2} \qquad (101)$$

where Ri_m = measured Richardson number; T_{v2}, T_{v3} = virtual temperature at 2 m and 3 m (K) and u_2, u_3 = wind speed at 2 m and 3 m (m s^{-1}). Virtual temperatures were computed from observed temperatures as:

$$T_v = T\ /\ [1 - (1-\varepsilon)e_a/P] \qquad (102)$$

where T and T_v are in K. In the second stage, the measured Richardson number was used to estimate an average value, representative of the layer between the surface and 2 m. Assuming that the Richardson number varies linearly with z-d_m, Ri_{avg} became:

$$Ri_{avg} = Ri_m * (2-d_m)/(3-d_m+2-d_m) \qquad (103)$$

The second procedure was based on an iterative solution of the energy balance equation:

$$R_n - G - E - \rho\ C_p\ (T_o - T_a)/r_a'' = 0 \qquad (104)$$

In the above equation, all variables except T_o were measured and r_a'' represented an aerodynamic resistance corrected for stability on the basis of an average Richardson number computed from:

$$Ri_{avg} = \frac{2\ g\ (T_{v2} - T_{vo})\ (2 - d_m)}{(T_{v2} + T_{vo})\ u_2^2} \tag{105}$$

where T_{vo} = virtual temperature at the effective surface (K). The virtual temperature at the effective surface was computed in two ways: by assuming that the humidity at the surface was equal to the humidity at 2 m and by assuming that the effective surface was saturated. The substitution of Eqs. 105 and 96 through 100 into Eq. 104 led to an implicit expression for T_{vo}, which was solved by the Newton-Secant method.

The use of a simplified stability correction such as Eq. 96 may seem surprising in view of the availability of more exact formulations (Eq. 39). It should be kept in mind, however, that the purpose of this procedure was merely to evaluate the potential value of a stability correction, obtained from limited information.

The influence of environmental factors on surface resistance was investigated by estimating the period of full cover and then plotting surface resistances for this period against temperature, vapor pressure, vapor pressure deficit, wind speed, solar radiation and Bowen ratio.

The procedures outlined above were used to compute surface resistances from both hourly and daily average data. For comparative purposes, hourly surface resistances were averaged into daily values in several ways. First, by means of a direct average, giving an equal weight to all hourly resistances, and secondly, by means of a weighted average, using either solar radiation, net radiation or lysimeter evapotranspiration as a weight. Both an arithmetic and an harmonic average were tried. They are defined as:

$$r_{sa} = \frac{\Sigma\ w_i\ r_{si}}{\Sigma\ w_i} \tag{106}$$

and

$$r_{sh} = \frac{\Sigma\ w_i}{\Sigma\ w_i/r_{si}} \tag{107}$$

where r_{sa} = arithmetic average surface resistance (s m^{-1}), r_{sh} = harmonic average surface resistance (s m^{-1}), r_{si} = hourly surface resistance (s m^{-1}) and w_i = weight. In order to obtain a direct average, w_i was set to 1.

Soil Resistance. Soil resistance was computed by means of the same procedure as for surface resistance. An additional problem, however, was the determination of the aerodynamic properties of the bare soil. Equations 92 and 94 may be valid for a vegetated surface, but are definitely invalid for a bare soil. d_m and d_s were both set to 0 for a bare soil. The values of z_{om} and z_{os}, on the other hand, were estimated by iteration: Eq. 94 was assumed to be valid for a bare soil too (which is not the case because vegetation is flexible and semi-permeable, whereas the soil surface is rigid and bluff) and z_{om} was varied until the back-calculated soil resistance was somewhere between 0 and 50 s m^{-1} on the first few days after irrigation. The value of z_{om} obtained by this procedure will be referred to as the apparent roughness length for a bare soil. The specification "apparent" indicates that this value has no true physical significance, but merely represents the roughness that should be attributed to a bare soil, in order to be able to describe its aerodynamic behavior by means of a relation that is only applicable to permeable bodies (Eq. 94). Reverting to an apparent roughness length may seem unnecessary because relationships for the estimation of aerodynamic properties of bare soils are available in the literature. These relationships do, however, require knowledge of the clod size. Because this information was not available, the use of literature relationships for z_{om} and z_{os} could only have resulted in an iteratively estimated clod size. Once again, all calculations were carried out on both an hourly and a daily basis.

Evaluation of Models

The Kimberly-Penman Model

The Kimberly-Penman equation was used to compute crop evapotranspiration from the daily data obtained at the U.S. Weather Service station. These data were not modified, except for solar radiation. A comparison of solar radiation with clear sky solar radiation revealed that solar radiation readings for 1973 and 1974 were too high. Therefore, these values were replaced by those published by Wright (1978). The data set was expanded by adding the measurements of lysimeter evapotranspiration as well as the estimates of precipitation read from lysimeter charts. The meteorological data used in this evaluation were the same as those originally used by Wright (1982). The lysimeter measurements of evapotranspiration, on the other hand, may be slightly different: Wright (1982) used daily totals which were read manually from lysimeter charts, whereas this study used the values recorded electronically by a data acquisition system.

Reference evapotranspiration was computed according to the procedures outlined in Chapter 3 (Eqs. 1 through 26). Crop evapotranspiration was computed by multiplying reference evapotranspiration by a crop coefficient obtained from Eqs. 28 and 30. The dates of the key growth stages required for the application of the basal crop coefficients listed in Table 1 were taken from Table 3. As suggested by Wright (1982), the actual dates of planting and emergence for winter wheat were replaced by effective dates, namely February 15 for planting and March 1 for emergence. Furthermore, field notes indicated that in 1978, the wheat on the lysimeter ripened much later than the wheat in the lysimeter field. The basal crop coefficients listed in Table 1 appear to reflect the phenology of the field wheat. In order to obtain a better approximation of the phenology of the wheat on the lysimeter, ripening was postponed by inserting an extra 10 days of full cover.

It was assumed that all crops were never short of water. As a result, the soil moisture reduction factor K_a was not taken into consideration.

The wet soil evaporation term K_s was computed from Eq. 30. In this equation, t_d was assumed to be 5 days (silt loam) and f_w was taken as 1 for rain and 0.75 for furrow irrigation. Whenever a wetting took place before noon, t_w was set to 0 on the same day, but when a wetting took place after noon, t_w was set to 0 on the next day. All minor wettings of less than 3 mm were ignored. In order to prevent an overestimation of wet soil evaporation after a minor wetting event, a temporary sum of evaporation (= $\Sigma K_s ET_r$) was initiated after each wetting. Whenever the cumulative evaporation threatened to exceed the total moisture applied, the wet soil evaporation spike was terminated prematurely, i.e. before t_w reached t_d.

The overall performance of the Kimberly-Penman method was evaluated by means of two parameters: the ratio of computed seasonal evapotranspiration to measured seasonal evapotranspiration and the root mean squared error, defined as:

$$RMSE = \sqrt{\Sigma(ET_c - ET_m)^2/N} \qquad (108)$$

where RMSE = root mean squared error (mm day^{-1}), ET_c = crop evapotranspiration (mm day^{-1}), ET_m = measured evapotranspiration (mm day^{-1}) and N = number of measurements. The first parameter measures the accuracy of the model on a seasonal basis, whereas the second one gives an indication of the quality of the daily estimates.

The Penman-Monteith Model

Two different models of the Penman-Monteith type were used to directly compute crop evapotranspiration. The first model (henceforth indicated as model I) followed the approach outlined by Jordan and Ritchie (1971). The second model was based on the approach of Grant (1975) and the modifications suggested by Thompson et al. (1981), and will be referred to as model II. In both cases, the basic approach (the core of the model) was obtained from the sources quoted above. The specific implementations presented in this study, however, were arrived at by the author by combining these approaches with information obtained from other literature sources, as well as a number of original contributions.

All calculations were carried out on a daily basis by means of the daily average data obtained at the USDA-ARS lysimeter site. This data set contained values of e_a, T_a, u, R_n and G which were measured above (or below) the crop under study. In both models, ρ_a, C_p, Δ, γ and e_s were computed from Eqs. 32, 14, 9, 11 and 7 respectively.

Aerodynamic resistance was computed from equation 39, but stability corrections were omitted. Zero plane displacement and roughness length for momentum were estimated as 0.67 and 0.10 times the crop height. The ratio of scalar roughness to momentum roughness was assumed to be 0.2 and the zero plane displacement for scalars was assumed to be equal to the zero plane displacement for momentum. For a bare soil, an apparent roughness length of 5 mm was used and zero plane displacement was set equal to zero.

In model I, total surface resistance was computed from Eq. 55. Plant resistance was computed from Eqs. 46 through 48 assuming that the leaf resistance of a fully illuminated leaf equaled 100 s m^{-1} (Allen et al., 1989) and that the maximum effective leaf area index equaled 4. Soil resistance was assumed to be 50 s m^{-1} after a significant wetting (at least 3 mm) and was then increased as a quadratic function of time to a maximum value of 2000 s m^{-1} five days after wetting. In the case of incomplete wetting, dry and wet soil were placed in parallel:

$$1/r_{ss} = f_w/[50+1950*(t_w/t_d)^2] + (1-f_w)/2000 \qquad (109)$$

Percent cover was estimated on the basis of archive slides. These indicated that for beans, complete ground cover was obtained at a leaf area index of about 2.5, whereas in the case of wheat, complete ground cover required a leaf area index of about 3. "Complete ground cover" was estimated to have occurred at the time when the entire lysimeter surface was covered by plants and little or no soil remained visible. The dates on which complete ground cover was estimated to have been attained were compared to those listed for "effective full cover" by Wright (1982) (see Table 3). For snap beans and spring wheat, "complete ground cover" and "effective full cover" were found to be in excellent agreement. For winter wheat, on the other hand, "effective full cover" coincided with heading and took place much later than "complete ground cover", at a time when leaf area index was already over its maximum and was declining. The fact that beans attained complete ground cover at a lower leaf area index than wheat is probably the result of differences in leaf structure: bean leaves have a more horizontal position than wheat leaves and therefore are more effective in shading the ground. Prior to emergence, percent cover was set to zero. After emergence, cover was increased proportional to leaf area index until complete ground cover was attained. From then on, cover was assumed to remain complete until harvest.

In model II, total surface resistance was computed from Eq. 56 instead of Eq. 55. The plant resistance of a fully developed green canopy was assumed to be 25 s m^{-1}. This figure corresponded to $r_{ls}/(LAI_{max}/2)$ (with r_{ls} = 100 s m^{-1} and $LAI_{max}/2$ = 4) and was therefore consistent with the values used in model I. Soil resistance was computed in the same manner as for model I (Eq. 109). Following Grant (1975), the radiation extinction coefficient was assumed to be equal to the solar radiation extinction coefficient. This coefficient is equal to about 0.85 for beans and 0.70 for wheat (Monteith and Unsworth, 1990). The larger value for beans once again indicates that bean plants are more effective in intercepting radiation than wheat plants. In his original model, Grant (1975) suggested using the green leaf area index in Eq. 56. Thompson et al. (1981) pointed out that for cereals towards harvest, green leaf area index may be quite different from total leaf area index. Plant resistance is related to green leaf area index, but radiation interception should be a function total leaf area index. They therefore proposed to use total leaf area index in Eq. 56 and to account for the effects of ripening by gradually increasing the full cover plant resistance. For this purpose they suggested a third degree polynomial function that increased full cover plant resistance as a function of time since attainment of full cover. In model II, the decline of green leaf area index was used as an indicator of ripening for both beans and wheat. It was assumed that as long as green leaf area index was increasing, green leaf area index equaled total leaf area index and full cover plant resistance was set to its minimum value of 25 s m^{-1}. As soon as green leaf area index began to decline, ripening was assumed to take place. During ripening, leaves turn yellow and some may be dropped. Total leaf area index was rather arbitrarily assumed to decrease linearly with time from its maximum value to two thirds of this value at harvest (no measurements were available). Green leaf area index, on the other hand, was decreased much more rapidly towards an estimated harvest value (very few measurements available). Since plant resistance varies inversely with green leaf area index, the increase in full cover plant resistance was estimated as:

$$r_{sc} = 25 * LAI_{gm}/LAI_{gr} \tag{110}$$

where LAI_{gm} = maximum green leaf area index attained by the crop under consideration, just before the onset of ripening ($m^2\ m^{-2}$) and LAI_{gr} = remaining green leaf area index ($m^2\ m^{-2}$).

Because of the discontinuities in the lysimeter data set, it was not possible to compute a temporary sum of evaporation in order to keep wet soil evaporation from exceeding the total available moisture. The field notes and lysimeter charts did, however, allow the determination of the occurrence and magnitude of all wettings. In other words, if a wetting took place on a day for which no meteorological data were available, it was not possible to compute evaporation for that day, but it was still possible to properly reset t_w.

The performance of both models was evaluated by means of the same parameters used for the evaluation of the

Kimberly-Penman method, namely the seasonal ratio of measured and computed evapotranspiration and the root mean squared error.

The Shuttleworth-Wallace Model

The Shuttleworth-Wallace model was also used to directly compute crop evapotranspiration. The general structure of the model described in this section was obtained entirely from Shuttleworth and Wallace (1985). As was the case for the Penman-Monteith models, the specific version implemented here, is the result of filling this framework with additional information from other literature sources and with some original work.

All calculations were carried out on a daily basis by means of the daily average data obtained at the USDA-ARS lysimeter site. e_a, T_a, u, R_n and G were measured above (or below) the crop under study and ρ_a, C_p, Δ, γ and e_s were computed from Eqs. 32, 14, 9, 11 and 7. The net radiation at the surface was estimated from Eq. 65. When applying this equation, it was assumed that the net radiation extinction coefficient equaled the solar radiation extinction coefficient. The latter was assigned a value of 0.85 and 0.70 for beans and wheat respectively (Monteith and Unsworth, 1990).

Aerodynamic resistance was computed from Eqs. 68 and 69. Zero plane displacement and roughness length for momentum for vegetated and bare surfaces were evaluated in the same manner as for the Penman-Monteith models. The minimum leaf area index required for a crop to be considered dense was assumed to be 4 (Shuttleworth and Wallace, 1985).

Plant resistance and soil resistance were estimated by means of the procedures described for Penman-Monteith model I. Bulk boundary layer resistance was computed by means of Eq. 70. In this equation, leaf boundary layer resistance was assigned a typical value of 12.5 s m^{-1} as suggested by Shuttleworth and Wallace (1985). Transfer resistance was obtained from Eqs. 74 and 75. The eddy diffusivity attenuation constant was assumed to be 2.5 for both beans and wheat (Monteith, 1973; Brutsaert, 1982).

Once again, a distinction had to be made between total leaf area index and green leaf area index. Plant resistance and bulk boundary layer resistance were computed by means of the effective green leaf area index. Net radiation penetration and transfer resistance, on the other hand, were evaluated on the basis of total leaf area index. Total and green leaf area index were estimated in the same way as for the Penman-Monteith models.

The Shuttleworth-Wallace model too, was evaluated by means of the seasonal ratio of computed and measured crop evapotranspiration and the root mean squared error.

Estimation of Input Variables

Introduction

The evaluations of the Penman-Monteith and Shuttleworth-Wallace models described in the previous section were based on the data obtained at the USDA-ARS lysimeter site. This data set was more extensive and of a better quality than most of the data available to the practicing engineer.

First, the meteorological data included measurements of both net radiation and soil heat flux. In practice, however, such measurements are seldom available. Therefore, an attempt was made to develop some algorithms to allow the estimation of these energy fluxes.

Secondly, all meteorological data were obtained above the crop under study and, most probably, inside the fully adjusted boundary layer. In practice, however, one usually has to settle for meteorological data obtained at the nearest weather station. In order to evaluate the magnitude of the errors introduced by using meteorological data from a grassed weather station as a substitute for measurements made above an agricultural crop, the measurements of temperature, vapor pressure, vapor pressure deficit and wind speed obtained at the USDA-ARS lysimeter site were compared to those from the U.S. Weather Service station.

Energy Fluxes

Net Radiation. Daily net radiation was estimated from the data obtained at the lysimeter site by means of procedures based entirely on the approach of Wright (1982). In a first step, Eqs. 16 through 25 were used to compute the albedo of a bare soil, a crop-soil mixture and a full cover crop. The net long wave radiation was computed from Eqs. 18 through 25 with the assumption that the emissivity of a crop-soil mixture is the same as the emissivity of a reference crop. The measured values of net radiation and solar radiation were then used to compute the albedo from Eq. 16, rewritten as:

$$\alpha_{cs} = 1 - (R_n + R_b)/R_s \qquad (111)$$

where α_{cs} = albedo of a crop-soil mixture.

In a second step, the values of albedo thus obtained were used as guidelines for the development of an algorithm to compute albedo and hence net radiation as a function of plant cover and soil moisture conditions. The general formula used for the albedo of a crop-soil mixture was (Thompson et al., 1981):

$$\alpha_{cs} = f_c\ \alpha_c + (1-f_c)\ \alpha_s \qquad (112)$$

where α_c = plant albedo and α_s = soil albedo.

Plant albedo was computed by choosing typical values at key growth stages (emergence, effective cover, ripening and harvest) taken from Table 3. Values for plant albedo on any other day were then obtained by linear interpolation between the values for the enclosing key growth stages. Plant albedo at emergence was arbitrarily assumed to be 0.25, whereas the plant albedos at the remaining key growth stages were estimated on the basis of the back-calculated albedos (after attaining full cover, α_{cs} equals α_c).

Soil albedo was computed as the composite of a wet soil and a dry soil albedo:

$$\alpha_s = \alpha_{sm}\ f_w + \alpha_{sd}\ (1-f_w) \tag{113}$$

where α_{sm} = moist soil albedo and α_{sd} = dry soil albedo. The albedo of a moist, drying soil was assumed to vary linearly between the value for a fully wet soil and a fully dry soil over a given drying period:

$$\alpha_{sm} = \alpha_{sw} + (\alpha_{sd}-\alpha_{sw})\ (t_w/t_d) \tag{114}$$

where α_{sw} = wet soil albedo. For consistency with previous models and calculations, t_d was assumed to equal 5 days and f_w was set to 1 for rain and 0.75 for furrow irrigation.

<u>Soil Heat Flux</u>. Two approaches for the estimation of soil heat flux were considered. In both cases, measurements of soil heat flux obtained at 5 cm depth inside the lysimeter were used. These values were not corrected for heat storage in the top 5 cm of the soil.

The first approach consisted of computing the ratio of daily soil heat flux to daily net radiation from the data obtained at the lysimeter site. Subsequently, an attempt was made to correlate this ratio to fraction cover and soil moisture conditions.

The second approach was based on the method suggested by Wright (1982). First, Eq. 26 was rearranged to compute the soil heat coefficient C_s. Next, the correlation between the magnitude of this coefficient and fraction cover and soil moisture was investigated. Because of the discontinuities in the data obtained at the lysimeter site, the temperature records from the U.S. Weather Service station were used for this purpose.

Meteorological Observations

Temperature. Two values for daily average temperature were compared. The first value was the daily average temperature measured at 2 m at the lysimeter (computed as the average of 24 hourly values) and the second value was estimated from Eq. 10 using observations of minimum and maximum temperature at 1.35 m at the weather station.

Vapor Pressure. The two values of vapor pressure used in the comparison were the daily average vapor pressure measured at 2 m at the lysimeter (computed as the average of 24 hourly values) and the vapor pressure computed by means of Eq. 6 from the dew point temperature at 1.35 m measured at 8 am at the weather station.

Vapor Pressure Deficit. Vapor pressure deficit was computed in the following two ways: first, as the average of 24 hourly deficits, each of which was computed from hourly average measurements of temperature and vapor pressure at 2 m at the lysimeter and secondly, from Eqs. 7 and 8 and the measurements of minimum, maximum and dew point temperature at the weather station.

Wind Speed. The values of wind speed used in the comparison were the daily average wind speed measured at 2 m at the lysimeter (computed as the average of 24 hourly values) and the daily average wind speed measured at 3.66 m at the weather station, adjusted to a 2 m equivalent by means of Eq. 5.

CHAPTER V

RESULTS AND DISCUSSION

Determination of Resistances

Aerodynamic Resistance

Wind Profile Parameters. The results of the computation of zero plane displacement and roughness length for spring wheat by means of the iterative log-linear regression are shown in Figs. 3 and 4. Fig. 3 shows a considerable scatter in the values of d_m/h. This scatter was not related to wind speed and was probably the result of using too few wind speed measurements (only three). The values of z_{om}/h shown in Fig. 4 were computed by means of the d_m/h values of Fig. 3 and most of the scatter in z_{om}/h was probably induced by the scatter in d_m/h. To test this hypothesis, the values of z_{om}/h were recomputed, this time assuming that d_m/h was equal to the literature value of 0.67 for full cover. The results are shown in Fig. 5 and indicate that some of the scatter in Fig. 4 was indeed the result of using erroneous values of d_m/h. The average value of z_{om}/h was 0.076, and no dependency on wind speed was found. In order to evaluate the impact of the assumption made for d_m/h on the resulting value of z_{om}/h, the analysis was repeated for $d_m/h = 0.33$ and $d_m/h = 1.00$. The results are summarized in Table 4.

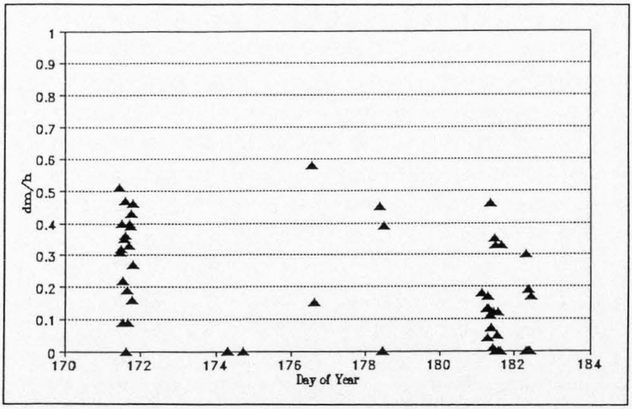

FIGURE 3. Zero Plane Displacement for Spring Wheat (1989).

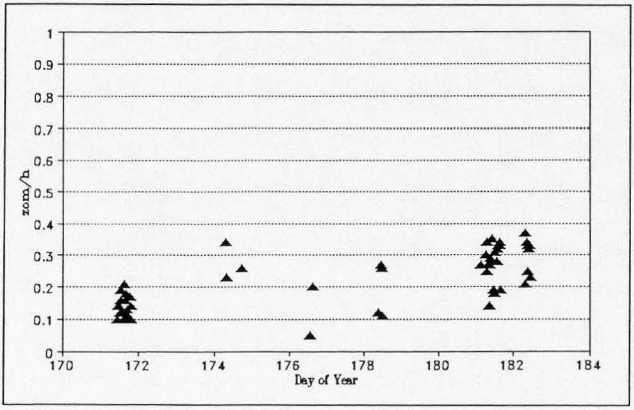

FIGURE 4. Roughness Length for Spring Wheat (1989).

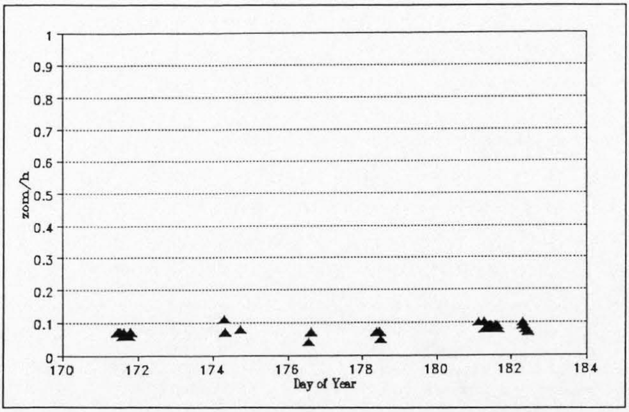

FIGURE 5. Roughness Length for Spring Wheat (1989) (Constant Zero Plane Displacement).

TABLE 4. Roughness Length, Method I (Spring Wheat, 1989).

	average	std. dev.	coeff. var.
d_m/h computed	0.221	0.087	39.4
$d_m/h = 0.33$	0.165	0.032	19.4
$d_m/h = 0.67$	0.076	0.013	17.1
$d_m/h = 1.00$	0.023	0.006	26.1

Table 4 includes the average, standard deviation and coefficient of variation (= 100*standard deviation/average) from all observations and shows that the average value of z_{om}/h is very sensitive to the assumptions made for d_m/h. The standard deviation gives an indication of the absolute scatter in z_{om}/h for each value of d_m/h, whereas the coefficient of variation quantifies the relative scatter in

z_{om}/h, allowing a comparison of the various assumptions for d_m/h. Since it is not known for sure whether z_{om}/h is a true constant or rather varies with factors such as wind speed or wind direction, the coefficient of variation should not be used to evaluate the quality of the d_m/h estimate, i.e. the approach for d_m/h which yields the lowest coefficient of variation for z_{om}/h is not necessarily the optimal one.

The results for d_m/h and z_{om}/h for snap beans are shown in Figs. 6 and 7 and show the same trend as for wheat: an enormous amount of scatter in the values of d_m/h and a smaller, but still significant amount of scatter in z_{om}/h. Once again, the observed values of d_m/h were disregarded and z_{om}/h was recomputed with $d_m/h = 0.67$. Fig. 8 shows that, in this case too, the scatter in z_{om}/h was largely removed. Strictly speaking, the value 0.67 only holds for full cover conditions and d_m/h should increase monotonically with density. In the case of wheat, full cover had already been established at the beginning of the observations, but the measurements on the beans started when the rows were only about 15 cm wide (with a row spacing of 56 cm). The field observations indicated that row width increased at the same rate as plant height, and that the rows were barely touching when plants reached their maximum height. Therefore, plant height was used as an indicator of percent cover and d_m/h was varied linearly with plant height from 0 at $h = 0$ to 0.67 at $h = h_{max}$.

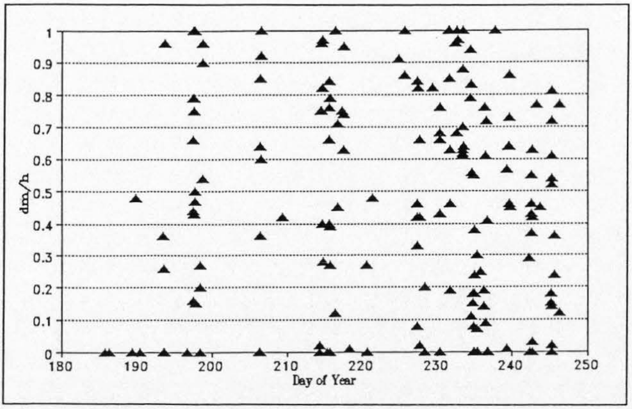

FIGURE 6. Zero Plane Displacement for Snap Beans (1989).

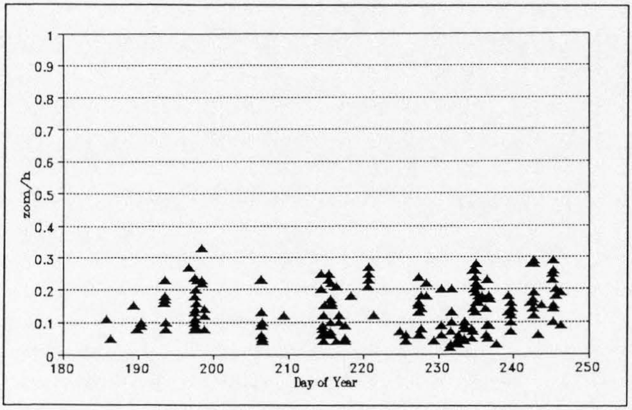

FIGURE 7. Roughness Length for Snap Beans (1989).

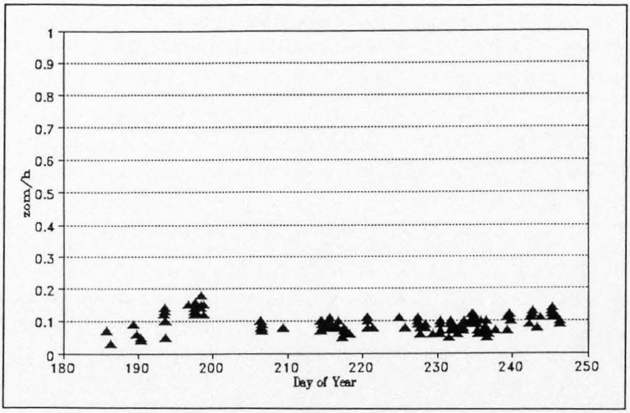

FIGURE 8. Roughness Length For Snap Beans (1989) (Constant Zero Plane Displacement).

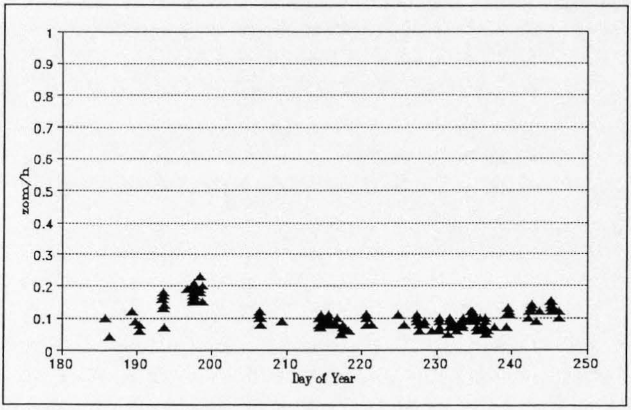

FIGURE 9. Roughness Length for Snap Beans (1989) (Variable Zero Plane Displacement).

The values of z_{om}/h obtained with a linearly varying d_m/h are shown in Fig. 9 and differ little from those in Fig. 8: the average value of z_{om}/h obtained with a constant d_m/h was 0.097 and the average z_{om}/h obtained with a variable d_m/h was 0.11. In both cases, no dependency on wind speed or wind direction was observed. It should be added that the wind direction measurements may have been in error, as a result of an improper averaging technique. Figs. 8 and 9 both suggest that z_{om}/h might have been higher at the beginning of the season when percent cover was low. A summary of the results of all determinations of z_{om}/h for snap beans is given in Table 5.

TABLE 5. Roughness Length, Method I (Snap Beans, 1989).

	average	std. dev.	coeff. var.
d_m/h computed	0.140	0.071	50.7
d_m/h = 0.33	0.159	0.033	20.8
d_m/h = 0.67	0.097	0.026	26.8
d_m/h = 1.00	0.054	0.021	38.9
d_m/h = f(h)	0.107	0.037	34.6

The determinations of zero plane displacement by means of Eq. 82 turned out to be a failure. In the case of the iterative log-linear regression, the methodology artificially limited the values of d_m to extremes of 0 and h. Equation 82, on the other hand, was not subjected to any such limitations and, on occasion, predicted values that were negative or several times h. This result seems to confirm the earlier observation that the use of only three wind speed measurements is insufficient for a reliable determination of d_m.

Because of the problems with Eq. 82, the determinations of roughness length by means of Eq. 83 were carried out with the assumptions for d_m/h described earlier. The results are shown in Fig. 10 for spring wheat with $d_m/h = 0.67$, Fig. 11 for snap beans with $d_m/h = 0.67$ and Fig. 12 for snap beans with $d_m/h = 0.67*(h/h_{max})$. All values shown are the average of three different computations, each based on a different two by two combination of the three available measurements.

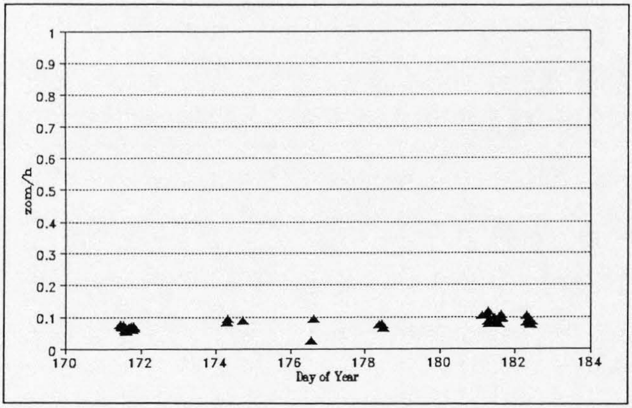

FIGURE 10. Roughness Length for Spring Wheat (1989) (Constant Zero Plane Displacement).

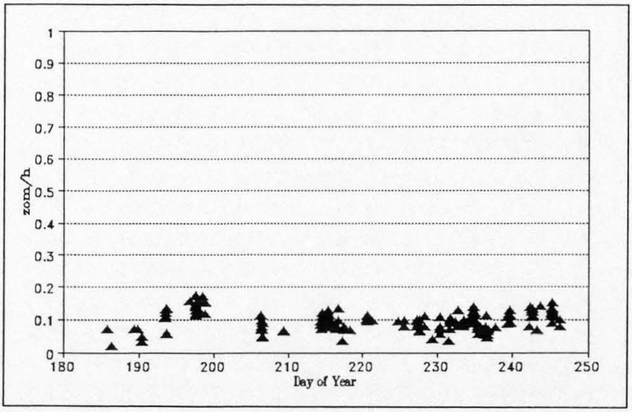

FIGURE 11. Roughness Length for Snap Beans (1989) (Constant Zero Plane Displacement).

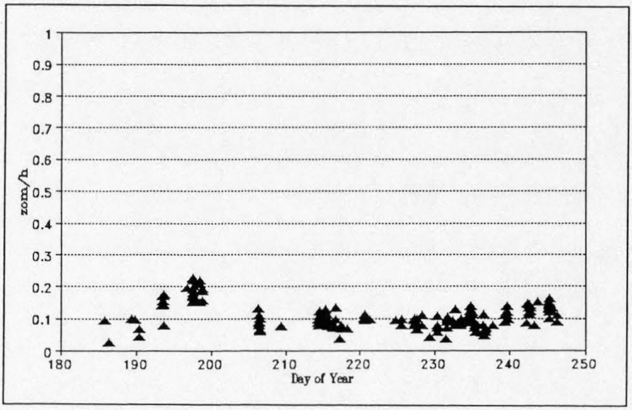

FIGURE 12. Roughness Length for Snap Beans (1989) (Variable Zero Plane Displacement)

The results agree very well with those of the log-linear regression and yield average z_{om}/h ratios of 0.080 for wheat with d_m/h = 0.67 and 0.098 and 0.11 for beans with d_m/h = 0.67 and $d_m/h = 0.67*(h/h_{max})$ respectively. Once again, no dependency on wind speed or wind direction was observed, but z_{om}/h again appears to have been slightly higher for beans during early growth. The statistics for the computations from Eq. 83 are shown in Tables 6 and 7 for spring wheat and snap beans respectively. They show very good agreement with the statistics in Tables 4 and 5.

TABLE 6. Roughness Length, Method II (Spring Wheat, 1989).

	average	std. dev.	coeff. var.
d_m/h computed	0.242	0.154	63.6
d_m/h = 0.33	0.165	0.037	22.4
d_m/h = 0.67	0.080	0.017	21.3
d_m/h = 1.00	0.029	0.007	24.1

TABLE 7. Roughness Length, Method II (Snap Beans, 1989).

	average	std. dev.	coeff. var.
d_m/h computed	0.218	0.322	147.7
d_m/h = 0.33	0.157	0.042	26.8
d_m/h = 0.67	0.098	0.031	31.6
d_m/h = 1.00	0.056	0.024	42.9
d_m/h = f(h)	0.108	0.041	37.8

Because the exact value of d_m/h could not be determined and the value of z_{om}/h was shown to depend strongly on the assumptions made for d_m/h, no conclusions could be drawn about the magnitude of either ratio, apart from the fact that the use of a literature value for d_m/h (0.67) leads to a value of z_{om}/h which is in good agreement with published values (0.10).

On the basis of previous considerations, all other calculations involving z_{om} or d_m throughout the remainder of this study were executed with the simple assumptions that $z_{om} = 0.10\ h$ and $d_m = 0.67\ h$ for both wheat and beans.

Aerodynamic Resistance. The comparison of measured and computed resistances, obtained from Eqs. 84 through 89 led to mixed results. The application of Eq. 86 was partly successful and yielded measured values of the order of magnitude of 10 s m^{-1} during daytime hours. In the early morning and late evening, the sensible heat flux tended towards zero (neutral conditions). As a result, the denominator of Eq. 86 became very small, and the resulting resistance became very large, sometimes positive and sometimes negative, depending on the signs of sensible heat flux and temperature gradient. At night, measured resistances exhibited a lot of scatter, occasionally turning negative.

The application of Eqs. 84 and 85, on the other hand, was judged to be completely unsuccessful: more than half of the measured values (including daytime values) turned out negative, a physically unacceptable result.

At first, the measured sensible heat flux was suspected to be the cause of the problem: it was indicated earlier that some of the instruments on the instrument tower may have caused distortions in the measured wind profiles. Instruments that are bulky enough to affect a cup anemometer are undoubtedly capable of strongly influencing atmospheric turbulence and therefore most probably also affected the readings from the sonic anemometer. Although tower wake effects are likely to have been part of the problem, there are two reasons for seeking an additional explanation elsewhere. First, negative values of aerodynamic resistance also occurred when the sonic anemometer was upwind of the tower and secondly, the application of Eq. 86 by means of the very same sensible heat flux gave reasonable results, especially during daytime hours. The successful application of Eq. 86 indicates that the sign of the measured sensible heat flux was probably correct, but the accuracy of its magnitude is unknown. The accuracy of measurements by means of a sonic anemometer depends on the relations between instrument characteristics (path length) and operation (sampling frequency, averaging period) and the local structure of atmospheric turbulence (size and frequency of eddies). In this study, no detailed analysis of these relationships was made, but all manufacturer's recommendations concerning installation and operation were adhered to. Therefore, no major errors in the magnitude of the measured fluxes are suspected.

If the sign of the measured sensible heat flux is accepted as reliable, one must turn towards the measured temperature gradients for an explanation of the observed anomalies. In Eq. 86, both temperatures were measured by means of identical thermocouples, referenced against each other and exposed to the environment in a similar fashion. Although the absolute values of each of these measurements may have been in error, the measured gradient had a very high degree of accuracy (few hundredths of a degree Celsius). In Eqs. 84 and 85, on the other hand, the upper temperature was measured by means of a thermocouple, whereas the lower one was obtained with an infrared radiometer. Errors in the absolute values of the readings from either instrument, could have seriously distorted the measured gradient.

The absolute values of the thermocouple readings may have been in error for a variety of reasons: radiation effects (thermocouples were not shielded), thermal gradients on the datalogger terminal strip or limited accuracy of the built-in datalogger thermistor, which served as a reference to determine absolute thermocouple temperatures.

The readings from the infrared radiometer may have been affected by surface emissivity, long wave radiation emitted by the atmosphere and reflected off the surface and instrument view angle. Surface emissivity was not changed from the factory-preset value of 0.98, which is supposed to be typical of a vegetated surface. It is possible that the true surface emissivity was different from this value, especially early in the season when large amounts of bare soil were exposed. In addition, part of the long wave radiation recorded by the infrared thermometer was not emitted by the surface, but rather emitted by the atmosphere and reflected off the surface. No attempts were made to correct the readings for this effect. Finally, in order to obtain a surface temperature which is a proper average of soil and plant temperatures, measurements should be made from the zenith. In this experiment, the infrared radiometer was positioned at a height of about 1 m with a zenith angle of about 30 degrees and an azimuth of 180 degrees. As a result of this view angle, part of the soil surface was masked by the plants and an improperly averaged apparent surface temperature may have resulted.

A final consideration is related to the nature of the surface temperature to be used in Eqs. 84 and 85. Ideally, one should use the temperature at the effective surface, rather than the radiative surface temperature. The former is a hypothetical temperature assigned to a hypothetical exchange plane and can therefore impossibly be measured. One might try to estimate it by extrapolation of the above canopy temperature profile (e.g. Monteith, 1963), but this would still require knowledge of the location of the effective surface. In a partial canopy with a dry soil surface, the locations of the sources or sinks for momentum, sensible heat and water vapor are all very likely to be different, making it very hard to determine the location of the effective surface.

A more thorough discussion of the effects of surface emissivity and reflected atmospheric long wave radiation on radiative measurements of surface temperature was given by Hipps (1989). More information on the effects of view angle and on the difference between radiative and aerodynamic surface temperature can be found in Huband and Monteith (1986).

Because the problems with the measurements led to physically unacceptable values for "measured" resistance, it was not possible to evaluate the accuracy of the aerodynamic resistance as computed from Eqs. 87 and 88.

Surface Resistance

Preliminary Work. The measured and estimated values of crop height and green leaf area index are shown in Figs. 13 through 16 for the growing seasons (planting to harvest) for beans (1973 and 1974) and wheat (1978 and 1979). In these figures, the symbols indicate individual measurements, whereas the curves represent continuous estimates.

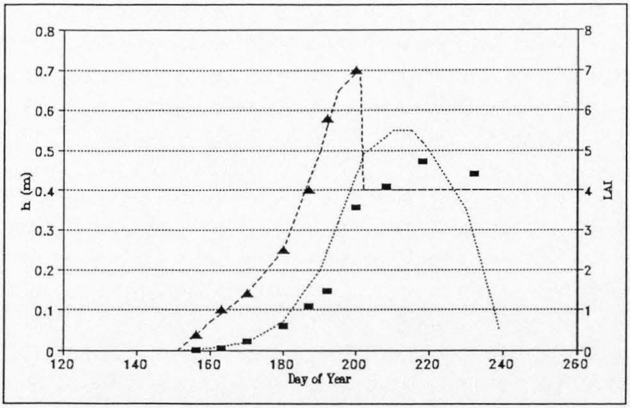

FIGURE 13. Crop Height (Δ) and Green Leaf Area Index (□)
(Snap Beans, 1973),
(from Wright, personal communication).

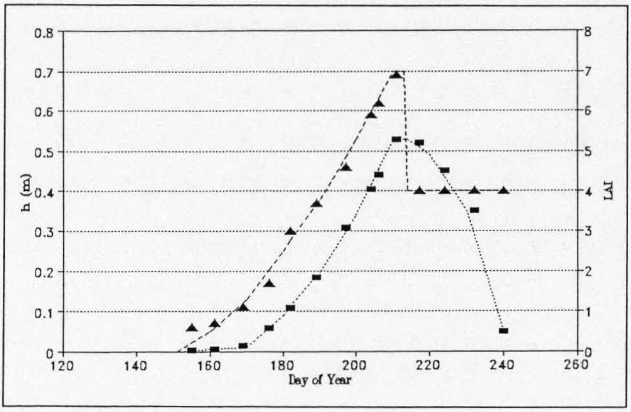

FIGURE 14. Crop Height (Δ) and Green Leaf Area Index (□)
(Snap Beans, 1974),
(from Wright, personal communication).

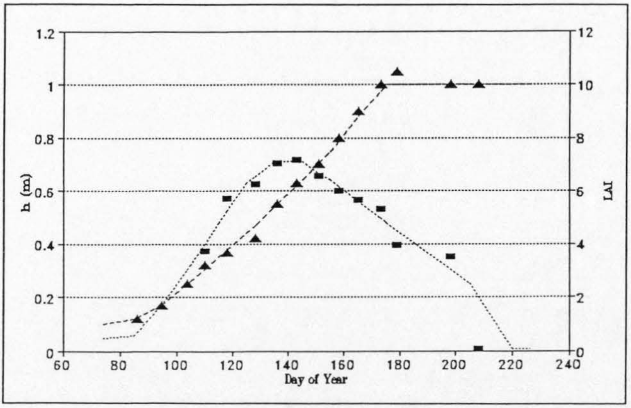

FIGURE 15. Crop Height (Δ) and Green Leaf Area Index (□) (Winter Wheat, 1978), (from Wright, personal communication).

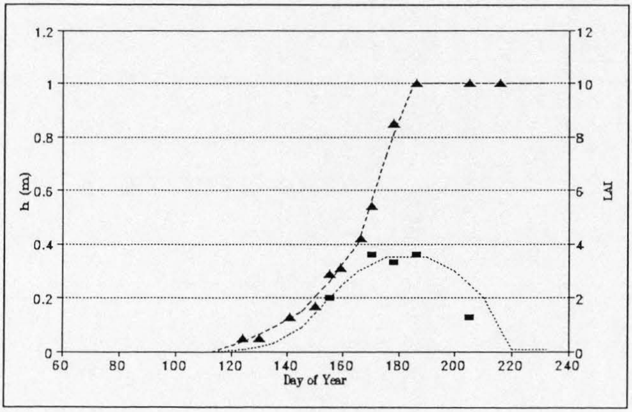

FIGURE 16. Crop Height (Δ) and Green Leaf Area Index (□) (Spring Wheat, 1979), (from Wright, personal communication).

The snap beans were of the variety 'Slim Green' and were unusually tall (up to 70 cm). The sudden reduction in height halfway through the season was the result of lodging. Crop height and leaf area index were very similar during the 1973 and 1974 growing seasons. The large differences between measured and estimated leaf area index for the 1973 season reflect an attempt to approximate lysimeter conditions.

The two wheat crops reached very similar heights (about 1 m), but their maximum leaf area index was quite different (more than 7 in 1978, about 3.5 in 1979). The large difference in maximum leaf area index resulted from differences in variety and planting time: the 1978 crop was a winter wheat (variety 'Nugaines') whereas the 1979 crop was a spring wheat (variety 'Fielder'). In both years, the differences between measured and estimated leaf area index towards harvest once again reflect attempts to approximate lysimeter conditions.

The adjusted values of daily evapotranspiration measured by lysimeter for the four growing seasons are shown in Figs. 17 through 20. For winter wheat (1978), the data obtained between planting and the melting of the last winter snow (March 15) were not used in the analysis.

Daily soil evaporation observed during the two bare soil drying sequences is shown in Fig. 21. In Fig. 22 measured evaporation is shown as a fraction of potential evaporation.

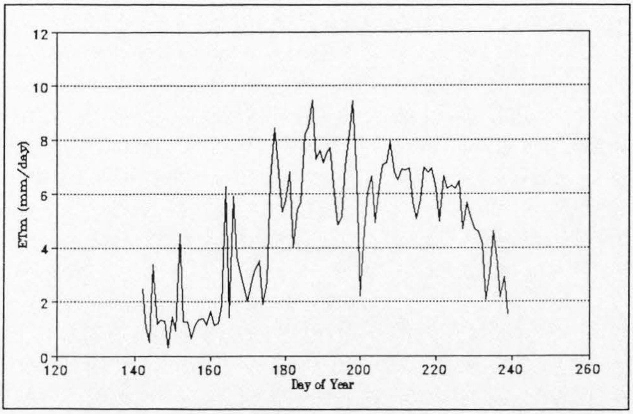

FIGURE 17. Measured Daily Evapotranspiration (Snap Beans, 1973), (from Wright, personal communication).

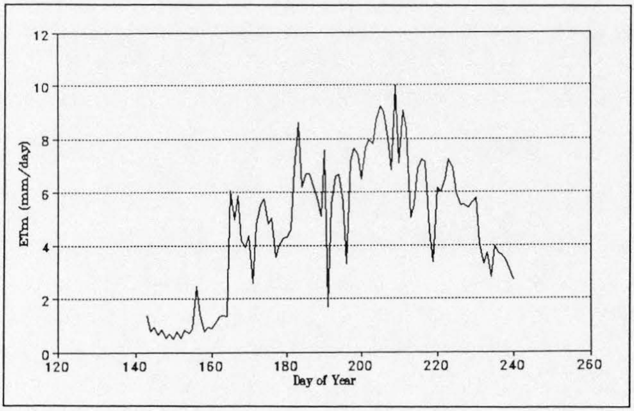

FIGURE 18. Measured Daily Evapotranspiration (Snap Beans, 1974), (from Wright, personal communication).

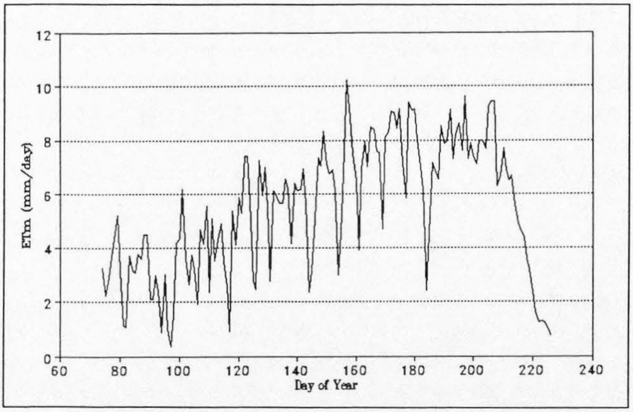

FIGURE 19. Measured Daily Evapotranspiration (Winter Wheat, 1978), (from Wright, personal communication).

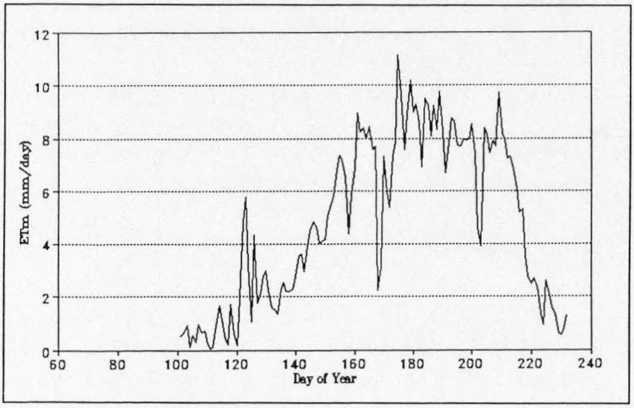

FIGURE 20. Measured Daily Evapotranspiration (Spring Wheat, 1979), (from Wright, personal communication).

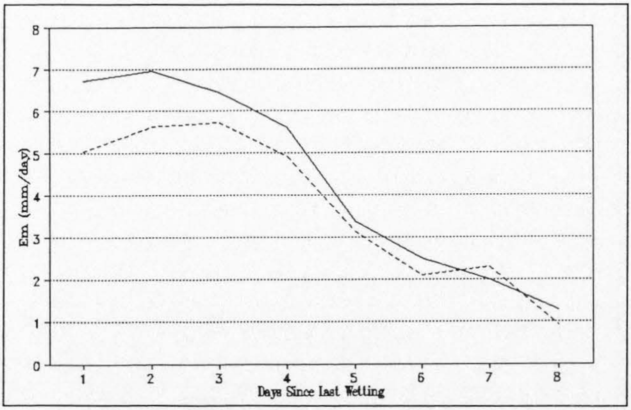

FIGURE 21. Measured Daily Evaporation (Bare Soil, 1977), First (—) and Second (···) Series, (from Wright, personal communication).

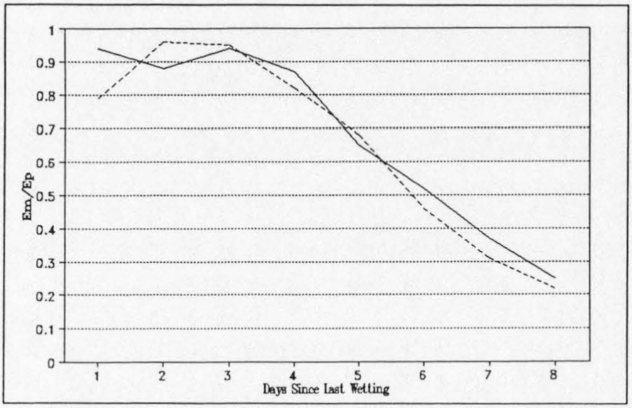

FIGURE 22. Daily Measured Evaporation as a Fraction of Potential Evaporation (Bare Soil, 1977), First (—) and Second (···) Series.

Potential evaporation for a saturated soil was computed from the Penman-Monteith equation, not corrected for stability, assuming no surface resistance (r_s = 0) and an apparent roughness length of 5 mm. Figs. 21 and 22 clearly show the existence of first and second stage drying. During the first stage, which lasted about three days, evaporation rates remained almost constant at a high value. During the second stage, evaporation rates dropped off steeply. The total amount of wet soil evaporation was 35 mm for the first sequence and 30 mm for the second sequence.

Surface Resistance. The values of surface resistance, back-calculated from daily average parameters by means of Eq. 90 are shown in Figs. 23 through 26. The values shown are those obtained with an aerodynamic resistance which was not corrected for stability. They have been listed in tabular form in Appendix B.

The overall seasonal trends for surface resistance corresponded to expectations: high in the early stages of development, decreasing to a minimum value at full cover and rising again towards harvest. The large scatter observed during the early growing season merely reflects variations in soil moisture and is no cause for alarm.

Resistances during full cover conditions exhibited quite some scatter and generally varied between 0 and 50 s m^{-1}. They occasionally assumed negative values, especially in the case of beans.

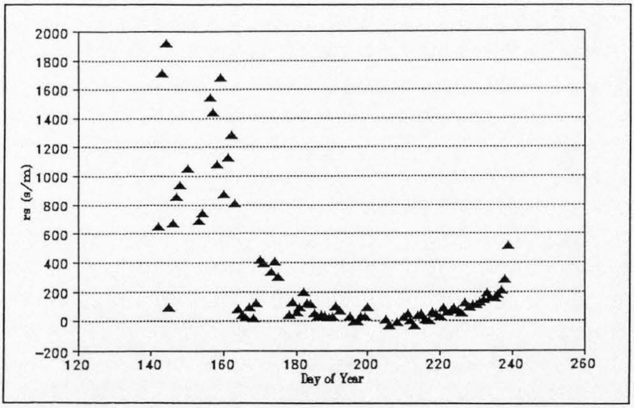

FIGURE 23. Computed Daily Surface Resistance (Snap beans, 1973).

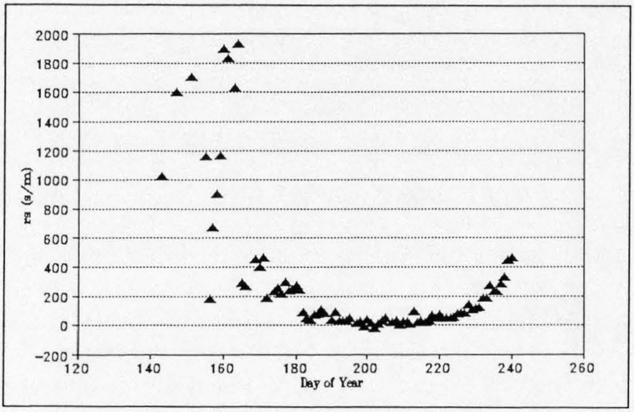

FIGURE 24. Computed Daily Surface Resistance (Snap Beans, 1974).

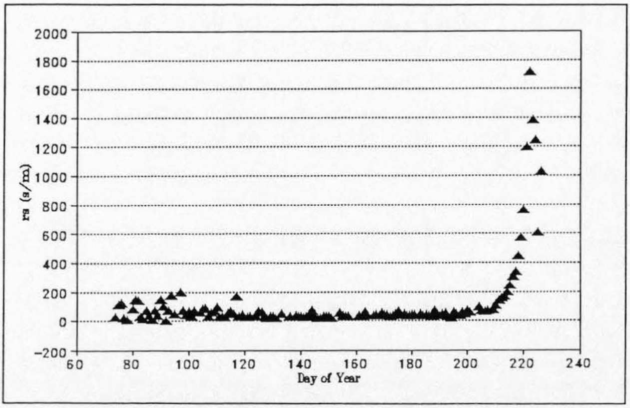

FIGURE 25. Computed Daily Surface Resistance (Winter Wheat, 1978).

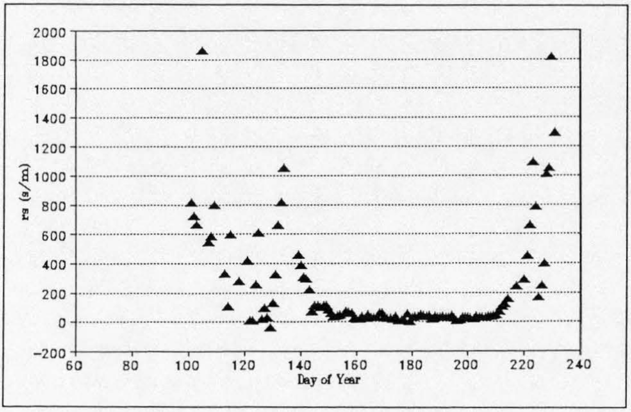

FIGURE 26. Computed Daily Surface Resistance (Spring Wheat, 1979).

Although there was no perfect pattern in the occurrence of these negative surface resistances, they do seem to have occurred most frequently on days with very low wind speeds (daily average wind speed less than 1.5 m s^{-1}) accompanied by strong advective conditions (daily evapotranspiration exceeding daily net radiation).

Several possible explanations for the occurrence of anomalous resistance values were investigated. The first possibility is that the negative resistances are the result of the use of an improper time scale: strictly speaking, the equation for aerodynamic resistance (Eq. 39) is only valid for periods up to an hour, whereas here it was applied to daily time periods. An investigation of the results of the hourly computations does, however, show that whenever daily surface resistances were negative, the corresponding hourly surface resistances were usually negative too. As a result, it is not likely that time scale effects are the main cause of the problem.

The second possibility is that surface resistances are in error because of the omission of a stability correction to the aerodynamic resistance term. In this case too, a closer examination seems to contradict this hypothesis. Most negative surface resistances occurred on days with strong advective conditions. Under such conditions, the incorporation of a stability correction into the aerodynamic resistance would have increased the aerodynamic resistance and hence (see Eq. 90) would have further decreased the already negative surface resistance.

A third possible explanation is related to the limited fetch. Since the fetch at the lysimeter site was only about 100 m, it is not impossible that some of the measurements obtained at a height of 2 m were made outside the fully adjusted boundary layer, especially during the early stages of development when the crop height was low and the field surface was smooth. The errors caused by measuring outside the fully adjusted boundary layer will depend on the nature of the upwind surface. When the upwind surface is rough and has a low evapotranspiration rate, measured temperatures will probably be too high and measured humidities will be too low. If, on the other hand, the upwind surface is rough with a high evapotranspiration rate, measured temperatures will probably be too low and measured humidities will be too high. The lysimeter field in which the data used in this study were obtained was surrounded by agricultural crops on all sides. On the west side (the predominant wind direction during the afternoon) it was bordered by alfalfa fields in 1973 and 1974, a barley field in 1978 and a spring wheat field in 1979. Most problem days, however, are characterized by low wind speeds and advection. Under these conditions, measurements made outside the fully adjusted boundary layer would be likely to yield temperatures which are too high and humidities which are too low. A look at Eq. 90 reveals that such conditions would lead to an overestimation of surface resistance rather than the observed underestimation. Therefore, limited fetch is also not believed to be the main problem.

The last possible explanation lies with the accuracy of the parameters describing the aerodynamic properties of the surface. Grant (1975) stated that Eq. 90 is not very sensitive to the accuracy of the aerodynamic resistance because γ/Δ is usually close to the Bowen ratio H/E, making the multiplier of the aerodynamic resistance almost zero. This reasoning only holds when there is no advection. Under advective conditions, the Bowen ratio is negative and the multiplier of aerodynamic resistance is a large negative number, rather than a small positive one. Therefore, under advective conditions, Eq. 90 is very sensitive to errors in the magnitude of aerodynamic resistance. Whenever aerodynamic resistance is too large, the resulting surface resistance will be too small and, in extreme cases, negative. Combining this reasoning with the earlier observation that unreasonable values of surface resistance seemed to occur under advective conditions combined with low wind speeds, indicates that the values of aerodynamic resistance computed on the basis of the assumptions stated in Eqs. 92 through 95 are probably too high for low wind speeds. If this hypothesis is correct, the observed problems could be remedied by assuming that roughness length increases to values larger than 0.1 h as wind speed decreases, or, alternatively, by assuming that the ratio of scalar roughness to momentum roughness increases to a value larger than 0.2 as wind speed decreases.

The first suggestion is most effective in reducing aerodynamic resistance at low wind speeds because it affects both momentum and scalar roughness. A relationship that predicts such a trend was given by Szeicz et al. (1969) (as cited by Verma and Barfield, 1979):

$$z_{om} = 0.1\ h\ (1.74\ u^{-0.608}) \tag{115}$$

This equation was derived from profile measurements above alfalfa and potatoes and predicts that z_{om}/h equals 0.1 for a wind speed of 2.5 m s^{-1} but increases to about 0.25 when u = 0.5 m s^{-1}. Equation 115 proved very effective in removing anomalous values of surface resistance but, unfortunately, the observations at Kimberly above spring wheat and snap bean crops described in the previous section (see Figs. 5, 8, 9 and 10) do not support the existence of such a trend. Verma and Barfield (1979) also voiced reservations about Eq. 115, indicating that it was derived from measurements which were not corrected for stability.

The second suggestion (variable ratio of z_{os} to z_{om}) is expressed in relationships proposed by Thom (1972). These relationships are:

$$z_{os} = z_{om}/\exp[k(1.35u_*^{1/3})] \tag{116}$$

and

$$z_{os} = z_{om}/\exp[k(2.30u_*^{1/3}-2.5)] \qquad (117)$$

Equation 116 was developed by Thom (1972) on the basis of measurements above field beans and Equation 117 was derived by Thom (1972) from earlier work by Cowan (1968). In this study, the friction velocity u_* was estimated from the logarithmic wind profile as:

$$u_* = k\ u\ /\ \ln((2-d_m)/z_{om}) \qquad (118)$$

Eq. 116 and 117 predict that the ratio of z_{os} to z_{om} may increase to more than 0.3 for $u_* = 0.1$ m s^{-1} and may decrease to less than 0.1 for $u_* = 1.0$ m s^{-1}. Unfortunately, the application of these relations only resulted in a very minor alleviation of the problems with surface resistance. Moreover, most problem values were observed with beans, after lodging, when the crop height itself was already very questionable. Therefore, the use of sophisticated expressions for z_{om}/h or z_{os}/z_{om} as functions of wind speed did not seem justified with the data sets available.

The problems with advective days are not surprising in view of the mechanism of advection and the way this mechanism is accounted for in the Penman-Monteith equation. The numerator of the Penman-Monteith equation features two terms: an energy (or radiative) term and an aerodynamic (or advective) term, which consists of vapor pressure deficit and aerodynamic resistance. Under non-advective conditions, the vapor pressure deficit of the air near the surface is usually small and the radiative term dominates the aerodynamic term. Under advective conditions, on the other hand, hot and dry air with a high vapor pressure deficit is transported toward the surface by atmospheric turbulence. This process results in an increase of the vapor pressure deficit near the surface and, as a consequence, in an increase of crop evapotranspiration. Under these conditions, the relative importance of the aerodynamic term increases. As a result, the Penman-Monteith equation is less sensitive to the accuracy of aerodynamic resistance under non-advective conditions than under advective conditions. Even under non-advective conditions, aerodynamic resistance still continues to influence the estimates of evapotranspiration through its presence in the denominator.

When investigating the influence of environmental factors (temperature, vapor pressure, vapor pressure deficit, wind speed, solar radiation and Bowen ratio) on full cover surface resistance, no clear trends were found. Subdividing the data into classes based on one variable, prior to plotting them against a second variable did not improve the situation. These observations confirm the suspicion that most of the variation in the values of surface resistance resulted from errors in the aerodynamic resistance, masking environmental influences. More detailed results have been included in Appendix C.

Hourly values of surface resistance, obtained by back-calculation from hourly average observations, exhibited even more scatter than their daily counterparts, especially during nighttime hours. A great deal of this scatter can undoubtedly be attributed to the inaccuracies in the measurement of the various energy fluxes (latent heat and net radiation). The results of the hourly computations for some typical days have been included in Appendix A.

The averaging of hourly surface resistances into daily averages did not yield useful results. Both direct and weighted harmonic averages were much too low. A direct arithmetic average, on the other hand, resulted in daily values which were too high because of the considerable influence of high nighttime values. A weighted arithmetic average yielded more acceptable values for daily resistance, but the results varied with the choice of weighting factor and contained a lot of scatter induced by outliers in the hourly resistances. An attempt was made to reduce this scatter by filtering the hourly resistances prior to averaging, i.e. by resetting all values below zero to zero and all values above some upper limit (e.g. 5000 s m^{-1}) to this upper limit. In this case, results turned out to be sensitive to the resistance limits used for the filter. Some results of this analysis have been included in tabular form in Appendix B. Because of the problems discussed above, the hourly surface resistances were not given any further attention.

As indicated earlier, the application of stability corrections on the basis of the procedures outlined in the previous chapter adversely affected the resulting surface resistances. The daily Richardson numbers computed from profile measurements at 2 and 3 m (Eqs. 101 and 103) were often not in agreement with the sign of the daily sensible heat flux obtained from the daily energy balance equation. For example, in the beginning of the growing season, the energy balance usually indicated that the days were non-advective (daily sensible heat flux was positive), but the average Richardson number was often positive, indicative of stable conditions and a negative sensible heat flux. It was suspected that part of this problem might have been caused by the use of virtual temperatures (computed from Eq. 102) rather than actual temperatures. The humidity at 2 and 3 m was measured by means of two different dew probes of the same type. Whenever the true humidity gradient was smaller than the instrument error, the use of a virtual temperature gradient instead of an actual temperature gradient might have resulted in erroneous Richardson numbers. In order to check this possibility, a comparison was made of the daily average measurements of vapor pressure at 2 and 3 m. This comparison revealed that the vapor pressures at 2 and 3 m were very similar for both bean crops (1973 and 1974), whereas for the wheat crops (1978 and 1979), the daily average vapor pressure at 2 m tended to be about 0.1 kPa higher than the daily average vapor pressure at 3 m. For beans, the Richardson numbers computed from actual temperature gradients and virtual temperature gradients were often different in magnitude, but always had the same sign. For wheat, on the other hand, the use of virtual temperature gradients instead of actual temperature gradients often converted positive Richardson numbers into negative ones. The Richardson numbers computed from virtual temperature gradients were usually in better agreement with the sensible heat flux obtained from the daily energy balance.

The iterative solution of the daily energy balance (Eq. 104) worked well on non-advective days and showed that the effect of a stability correction was usually negligible under these conditions. On strongly advective days, however, the procedure often failed to converge, especially when wind speeds were low. Large negative sensible heat fluxes required T_o to drop well below T_a. This created a large positive Richardson number which, when used to compute a stability correction to r_a', led to a significant increase in r_a''. The increased value of r_a'' then required T_o to drop even further. This process continued until Ri_{avg} exceeded the critical value (assumed to be 0.3) at which point the computations were interrupted. Both assumptions used for the estimation of surface humidity led to the same problem.

<u>Soil Resistance</u>. The evolution of soil resistance as a function of time since the last wetting is shown in Fig. 27. Both evaporation series followed exactly the same trend.

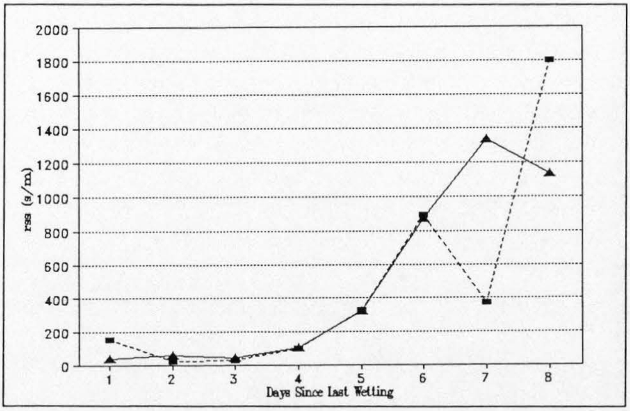

FIGURE 27. Computed Daily Surface Resistance (Bare Soil, 1977), First (—) and Second (···) Series.

The apparently anomalous value obtained on September 8 (7th day of the second sequence) may be the result of a measurement error. During this day, the field surrounding the lysimeter was cultivated in preparation for the planting of winter wheat. The field notes stated that the lysimeter was not disturbed in the process. However, inspection of the meteorological observations indicated that later that day very strong winds (> 7 m s^{-1}) occurred. These very strong winds may have affected the lysimeter readings and may even have moved loose soil particles formed during the cultivation.

Evaluation of Models

The Kimberly-Penman Model

The results of the application of the Kimberly-Penman method are shown in Figs. 28 through 35. A numerical summary of the performance is given in Table 8. At this point, the reader is reminded that all calculations for the Kimberly-Penman model were carried out on a daily basis by means of the data obtained at the U.S. Weather Service station. These data were the same ones used in the original development of the Kimberly-Penman method. The reference equation was originally presented by Wright (1982) and updated by Jensen et al. (1990). Basal crop coefficients were taken from Jensen et al. (1990), but were slightly modified in the case of winter wheat (1978). Key growth stages were obtained from Jensen et al. (1990), but were updated (see Table 3) on the basis of field notes in order to better reflect the specific crop under study (Wright, personal communication).

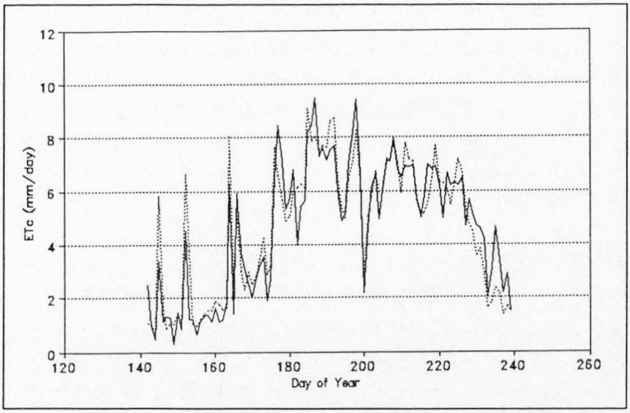

FIGURE 28. Measured (—) and Computed (···) Daily Evapotranspiration, Kimberly-Penman (Snap Beans, 1973).

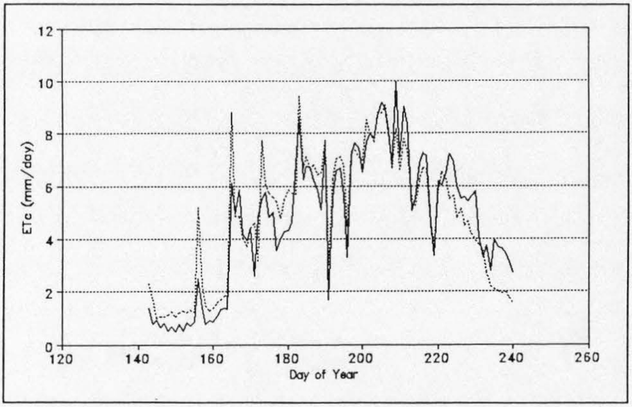

FIGURE 29. Measured (—) and Computed (···) Daily Evapotranspiration, Kimberly-Penman (Snap Beans, 1974).

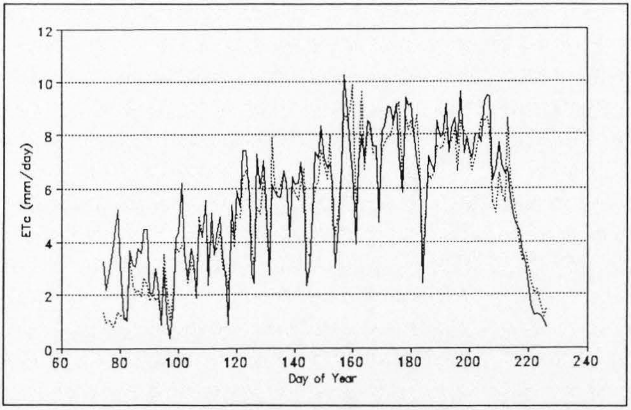

FIGURE 30. Measured (—) and Computed (···) Daily Evapotranspiration, Kimberly-Penman (Winter Wheat, 1978).

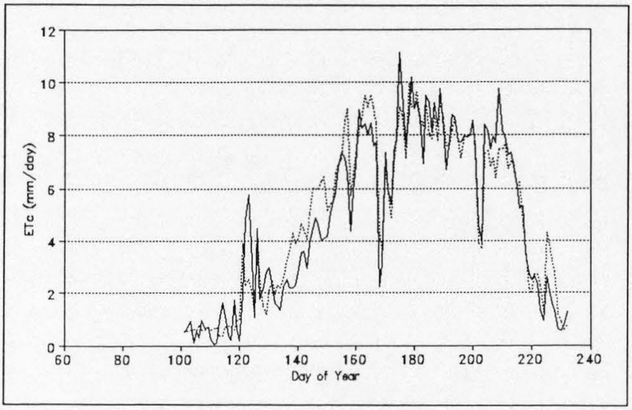

FIGURE 31. Measured (—) and Computed (···) Daily Evapotranspiration, Kimberly-Penman (Spring Wheat, 1979).

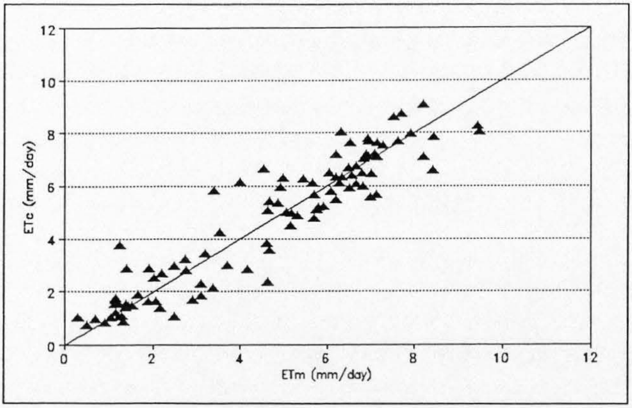

FIGURE 32. Computed versus Measured Daily Evapotranspiration, Kimberly-Penman (Snap Beans, 1973).

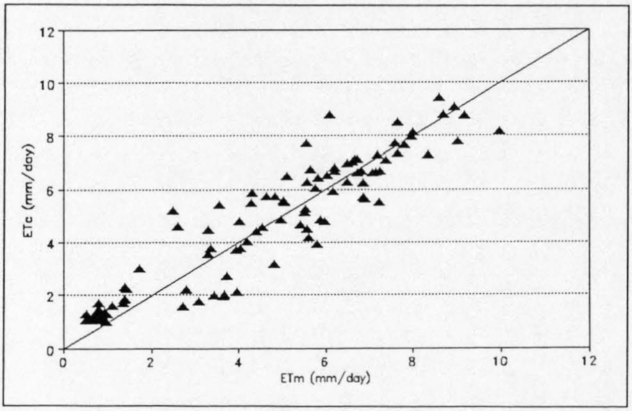

FIGURE 33. Computed versus Measured Daily Evapotranspiration, Kimberly-Penman (Snap Beans, 1974).

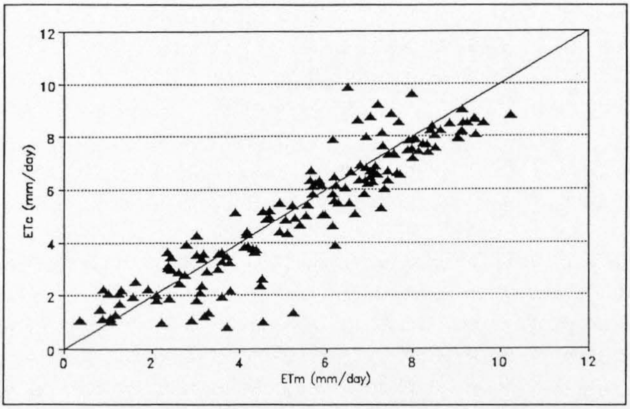

FIGURE 34. Computed versus Measured Daily Evapotranspiration, Kimberly-Penman (Winter Wheat, 1978).

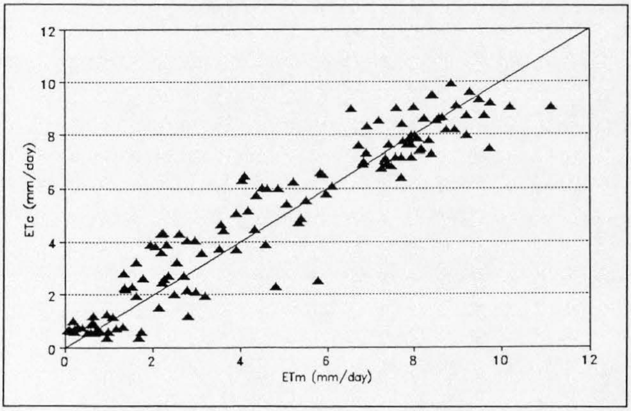

FIGURE 35. Computed versus Measured Daily Evapotranspiration, Kimberly-Penman (Spring Wheat, 1979).

Figures 28 through 31 show that, in general, measured and computed evapotranspiration agreed very well. In the case of beans (1973 and 1974), basal crop coefficients appear to have dropped off a little too soon towards harvest, whereas in the case of spring wheat (1979), they seem to have increased a little too fast after emergence. The largest discrepancy was observed for winter wheat (1978), right after initiation of growth in the spring, when computed evapotranspiration remained a lot below measured evapotranspiration. This probably indicates that the basal crop coefficient was too low for this period. Some of the computed wet soil evaporation spikes are too high. Since most of these excessive spikes are associated with irrigations, they indicate that, most probably, the estimate of f_w for furrow irrigations was too high for some irrigation events.

TABLE 8. Statistics for the Kimberly-Penman Model.

Crop	N	ΣET_m (mm)	ΣET_c (mm)	$\Sigma ET_c/\Sigma ET_m$	RMSE (mm d^{-1})
Snap beans 1	98	453	456	1.01	0.89
Snap beans 2	98	458	467	1.02	0.97
Winter wheat	153	833	796	0.96	1.04
Spring wheat	132	632	656	1.04	0.99

Table 8 shows that total seasonal evapotranspiration was estimated quite accurately: to within 5 percent. The root mean squared error (RMSE), on the other hand, is relatively high and indicates some error in the estimations for individual days.

In most years, the largest differences between measured and computed evapotranspiration seem to have occurred during periods with wet soil evaporation. To eliminate the effect of improperly estimated wet soil evaporation, the statistics shown in Table 4 were recomputed for days with basal conditions only (t_w>=5). The new results are shown in Table 9.

TABLE 9. Statistics for the Kimberly-Penman Model (Basal).

Crop	N	ΣET_m (mm)	ΣET_c (mm)	$\Sigma ET_c/\Sigma ET_m$	RMSE (mm d^{-1})
Snap beans 1	45	177	171	0.97	0.85
Snap beans 2	55	219	215	0.98	0.91
Winter wheat	91	534	503	0.94	1.10
Spring wheat	85	377	397	1.05	0.88

The results listed in Table 9 show that, when considering days with basal conditions only, the RMSE dropped in most years. This indicates that, for those years, a significant portion of the seasonal RMSE was indeed associated with errors in the estimation of wet soil evaporation. The winter wheat (1978) forms an exception. For this year, most of the error appears to have come from the severe underestimation just after regrowth. Elimination of non-basal days increased the weight of this period and increased the RMSE.

The Penman-Monteith Model

Model I. Penman-Monteith model I was used to directly compute crop evapotranspiration from the daily average data obtained at the USDA-ARS lysimeter site. The computation of surface resistance was modeled after Jordan and Ritchie (1971). Plant resistance was computed according to the recommendations of Szeicz and Long (1969) and the model for soil resistance was developed by the author. All remaining constants and parameters were obtained from various literature sources.

The results of the application of model I are presented in Figs. 36 through 43 and Table 10. They indicate that Model I did not perform as well as the Kimberly-Penman method. Figures 36 through 39 show that the seasonal trends in evapotranspiration were reflected correctly, but computed values tended to be too low early in the season and too high towards harvest. The latter was probably caused by the fact that plant resistance did not increase fast enough during ripening. In model I, plant resistance did not increase until the green leaf area index dropped below the maximum effective leaf area index of four. Furthermore, the model assumed that leaf resistance remained constant throughout the season. In other words, the model only accounted for the decrease in the total amount of green leaves, but did not allow for an additional decrease in quality of the remaining green leaves.

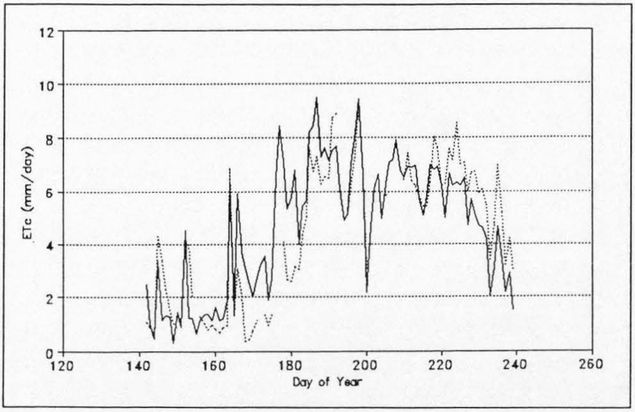

FIGURE 36. Measured (—) and Computed (···) Daily Evapotranspiration, Penman-Monteith I (Snap Beans, 1973).

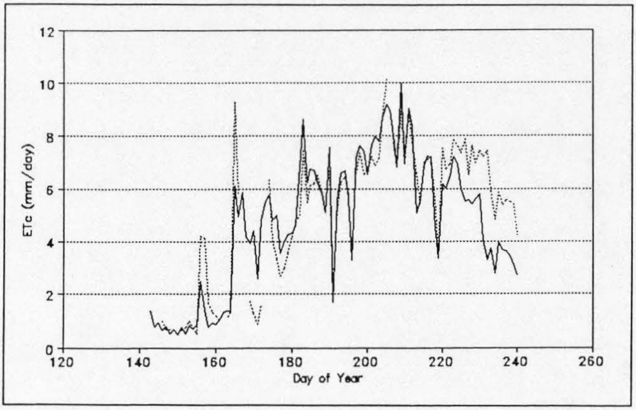

FIGURE 37. Measured (—) and Computed (···) Daily Evapotranspiration, Penman-Monteith I (Snap Beans, 1974).

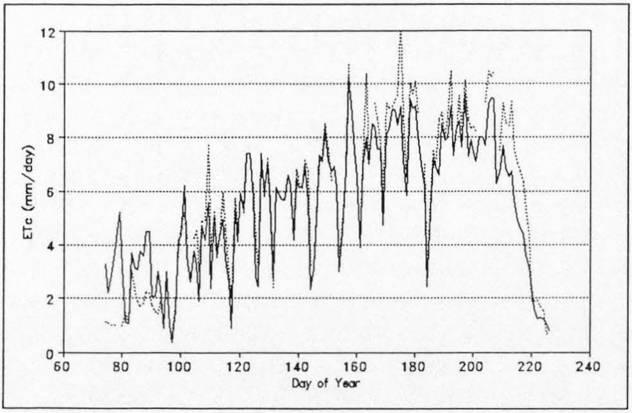

FIGURE 38. Measured (—) and Computed (···) Daily Evapotranspiration, Penman-Monteith I (Winter Wheat, 1978).

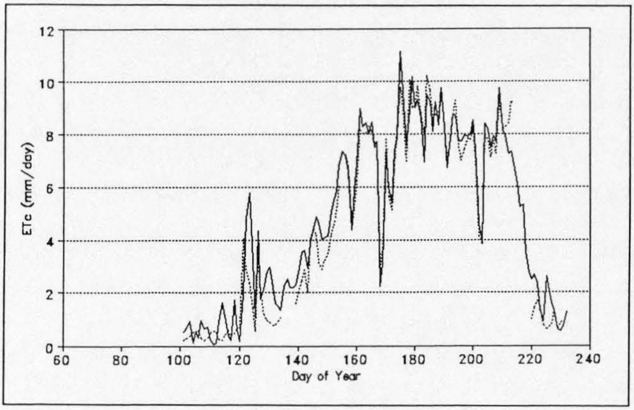

FIGURE 39. Measured (—) and Computed (···) Daily Evapotranspiration, Penman-Monteith I (Spring Wheat, 1979).

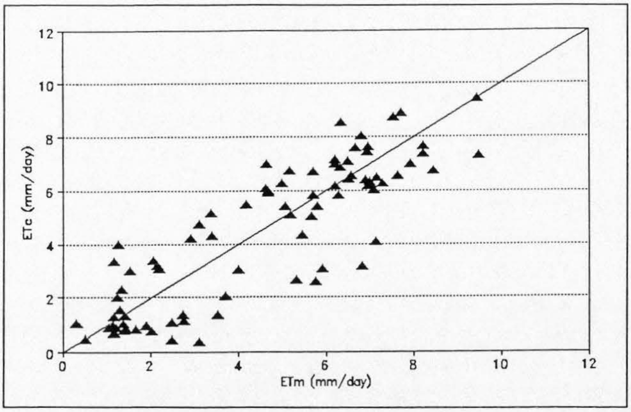

FIGURE 40. Computed versus Measured Daily Evapotranspiration, Penman-Monteith I (Snap Beans, 1973).

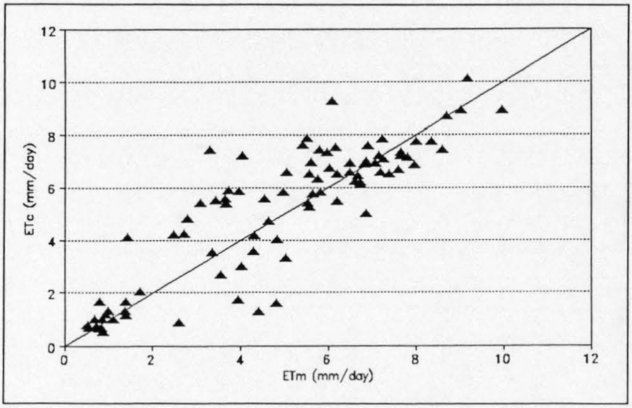

FIGURE 41. Computed versus Measured Daily Evapotranspiration, Penman-Monteith I (Snap Beans, 1974).

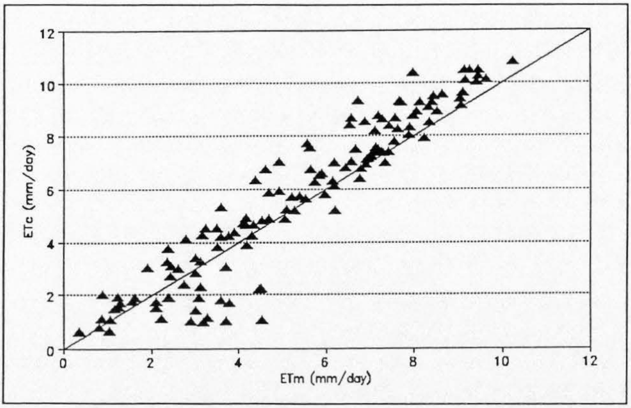

FIGURE 42. Computed versus Measured Daily Evapotranspiration, Penman-Monteith I (Winter Wheat, 1978).

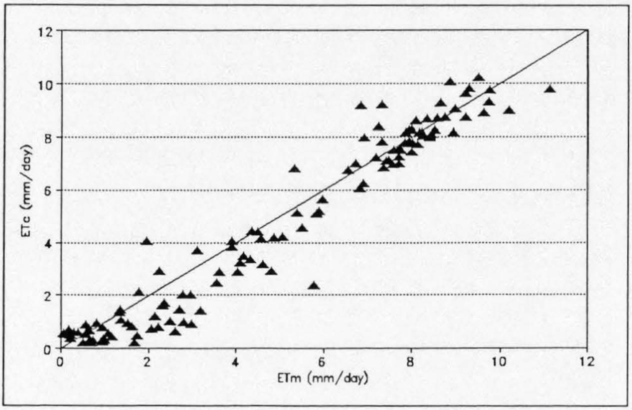

FIGURE 43. Computed versus Measured Daily Evapotranspiration, Penman-Monteith I (Spring Wheat, 1979).

TABLE 10. Statistics for Penman-Monteith Model I.

Crop	N	ΣET_m (mm)	ΣET_c (mm)	$\Sigma ET_c/\Sigma ET_m$	RMSE (mm d^{-1})
Snap beans 1	84	382	372	0.97	1.37
Snap beans 2	87	421	446	1.06	1.32
Winter wheat	134	714	763	1.07	1.13
Spring wheat	122	597	561	0.94	0.87

Table 10 shows that the seasonal estimates of evapotranspiration were almost as good as those of the Kimberly-Penman method. The daily estimates, however were much less reliable, as indicated by the higher RMSE. In general, daily estimates tended to be too low early in the season and too high towards harvest.

Because of discontinuities in the data set, it was not possible to keep an account of total soil evaporation after wetting. As a result, the estimates of evapotranspiration on days after a wetting are even more likely to have been in error than was the case for the Kimberly-Penman model. Therefore, for this model too, the performance of the model on basal days (t_w>=5) was evaluated separately. The results are shown in Table 11. Table 11 shows that excluding the non-basal days reduced the average RMSE in most years, but increased it in 1974. This indicates that for 1974, a lot of the error in the daily estimates occurred on basal days.

TABLE 11. Statistics for Penman-Monteith Model I (Basal).

Crop	N	ΣET_m (mm)	ΣET_c (mm)	$\Sigma ET_c/\Sigma ET_m$	RMSE (mm d^{-1})
Snap beans 1	43	173	170	0.98	1.25
Snap beans 2	48	198	218	1.10	1.49
Winter wheat	78	446	473	1.06	1.07
Spring wheat	75	342	329	0.96	0.73

Model II. Just like model I, model II was used to directly compute crop evapotranspiration from the daily average data obtained at the USDA-ARS lysimeter site. The computation of surface resistance was modeled after Grant (1975) and Thompson et al. (1981). The model for plant resistance during ripening, as well as the model for soil resistance were developed by the author. Once again, the values of all parameters and constants were obtained from various literature sources.

The results for model II are presented in graphical form in Figs. 44 through 51 and in tabular form in Table 12. Once again, a separate evaluation was made for basal conditions only (t_w>=5). The results are listed in Table 13.

TABLE 12. Statistics for Penman-Monteith Model II.

Crop	N	ΣET_m (mm)	ΣET_c (mm)	$\Sigma ET_c/\Sigma ET_m$	RMSE (mm d^{-1})
Snap beans 1	84	382	361	0.95	0.97
Snap beans 2	87	421	427	1.01	0.89
Winter wheat	134	714	708	0.99	0.63
Spring wheat	122	597	593	0.99	0.86

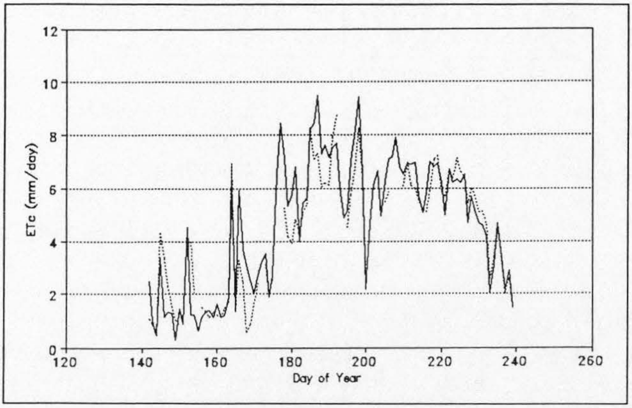

FIGURE 44. Measured (—) and Computed (···) Daily Evapotranspiration, Penman-Monteith II (Snap Beans, 1973).

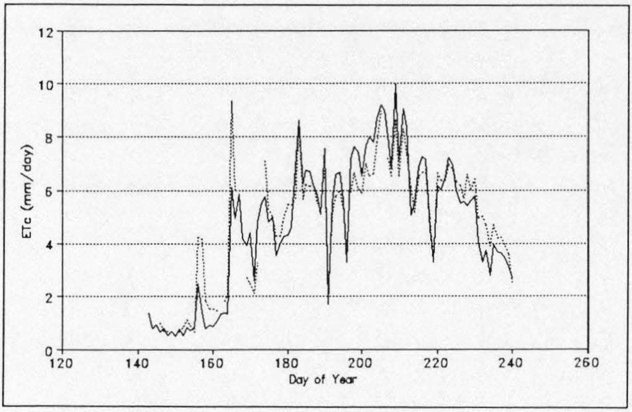

FIGURE 45. Measured (—) and Computed (···) Daily Evapotranspiration, Penman-Monteith II (Snap Beans, 1974).

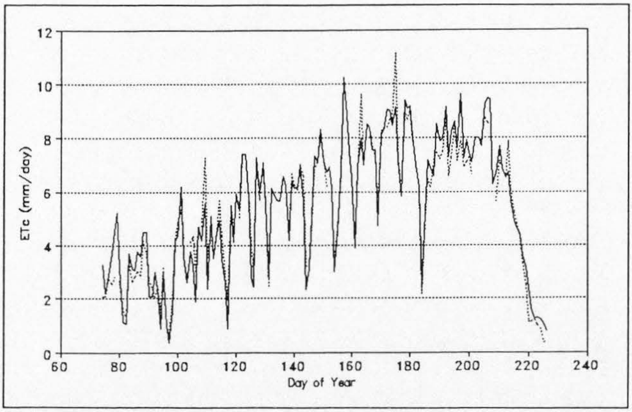

FIGURE 46. Measured (—) and Computed (···) Daily Evapotranspiration, Penman-Monteith II (Winter Wheat, 1978).

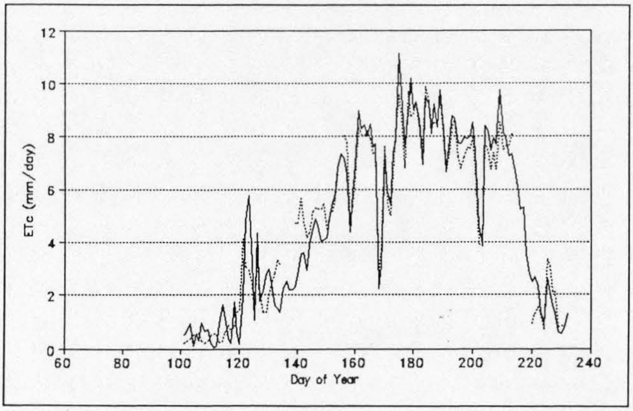

FIGURE 47. Measured (—) and Computed (···) Daily Evapotranspiration, Penman-Monteith II (Spring Wheat, 1979).

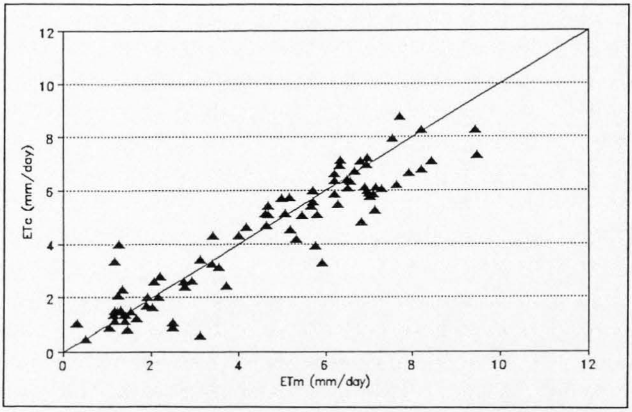

FIGURE 48. Computed versus Measured Daily Evapotranspiration, Penman-Monteith II (Snap Beans, 1973).

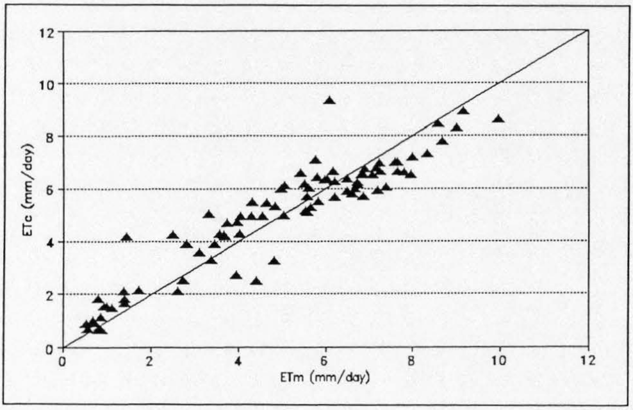

FIGURE 49. Computed versus Measured Daily Evapotranspiration, Penman-Monteith II (Snap Beans, 1974).

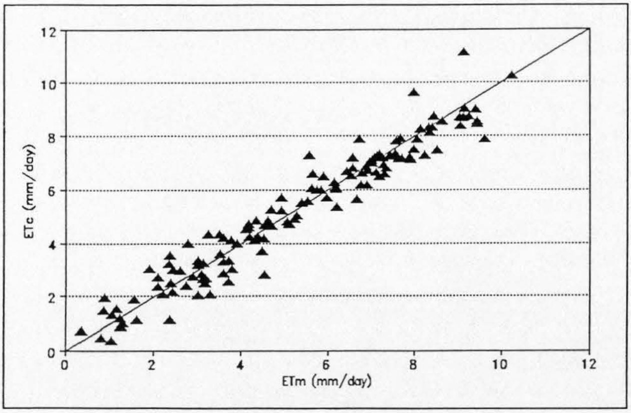

FIGURE 50. Computed versus Measured Daily Evapotranspiration, Penman-Monteith II (Winter Wheat, 1978).

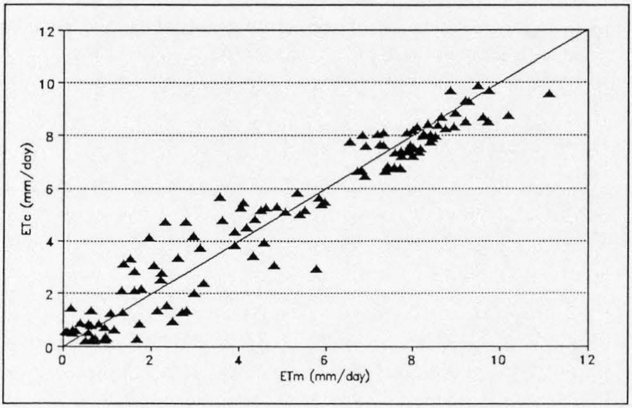

FIGURE 51. Computed versus Measured Daily Evapotranspiration, Penman-Monteith II (Spring Wheat, 1979).

TABLE 13. Statistics for Penman-Monteith Model II (Basal).

Crop	N	ΣET_m (mm)	ΣET_c (mm)	$\Sigma ET_c/\Sigma ET_m$	RMSE (mm d^{-1})
Snap beans 1	43	173	163	0.94	0.64
Snap beans 2	48	198	202	1.02	0.76
Winter wheat	78	446	432	0.97	0.58
Spring wheat	75	342	346	1.01	0.86

Tables 12 and 13 indicate that model II is considerably better than model I. Seasonal evapotranspiration was estimated quite accurately and, with the exception of 1973, the RMSE were less than for the Kimberly-Penman method. When considering basal conditions only, the RMSE were reduced even further.

The better performance of model II is probably related to the fact that it allowed ripening to influence plant resistance much earlier than model I. In model II, plant resistance started to increase as soon as green leaf area index started to decrease. In model I, on the other hand, plant resistance did not increase until green leaf area index decreased below four.

In model II, the sub-model for plant resistance during ripening was based on the assumption that individual leaf resistance remained constant throughout the season. The good results obtained with this assumption seem to contradict those from model I. As indicated earlier, the overestimation of crop evapotranspiration towards harvest by model I suggests that it might be desirable to increase individual leaf resistance towards harvest to account for the effects of leaf aging. Without the availability of reliable measurements of leaf resistance throughout the season, it is not possible to decide which approach is more justified.

The Shuttleworth-Wallace Model

The Shuttleworth-Wallace model too, was used to directly compute crop evapotranspiration from the daily average data obtained at the USDA-ARS lysimeter site. Plant resistance was modeled after Szeicz and Long (1969), the model for soil resistance was developed by the author and all other resistances were computed according to Shuttleworth and Wallace (1985). All constants required for the implementation of these resistances were obtained from literature sources.

The results of the application of the Shuttleworth-Wallace model are presented in Figs. 52 through 59 and Table 14. The results for basal conditions (t_w>=5) are listed in Table 15.

TABLE 14. Statistics for the Shuttleworth-Wallace Model.

Crop	N	ΣET_m (mm)	ΣET_c (mm)	$\Sigma ET_c/\Sigma ET_m$	RMSE (mm d^{-1})
Snap beans 1	84	382	410	1.07	1.19
Snap beans 2	87	421	483	1.15	1.22
Winter wheat	134	714	799	1.12	1.11
Spring wheat	122	597	623	1.04	0.87

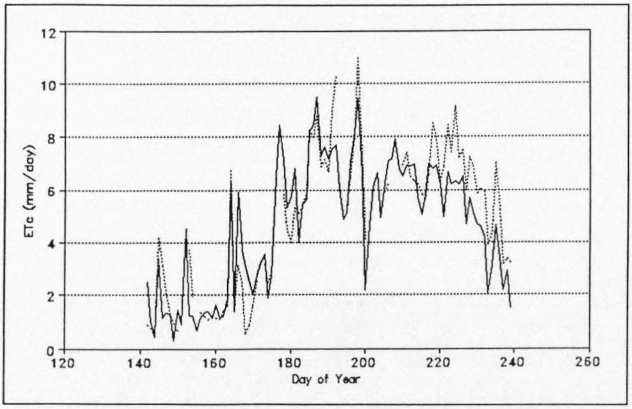

FIGURE 52. Measured (—) and Computed (···) Daily Evapotranspiration, Shuttleworth-Wallace (Snap Beans, 1973).

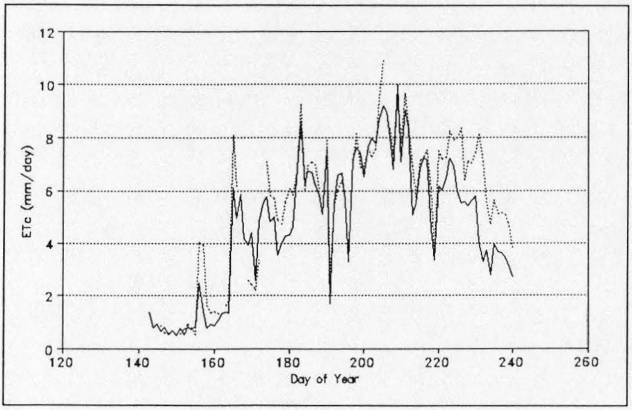

FIGURE 53. Measured (—) and Computed (···) Daily Evapotranspiration, Shuttleworth-Wallace (Snap Beans, 1974).

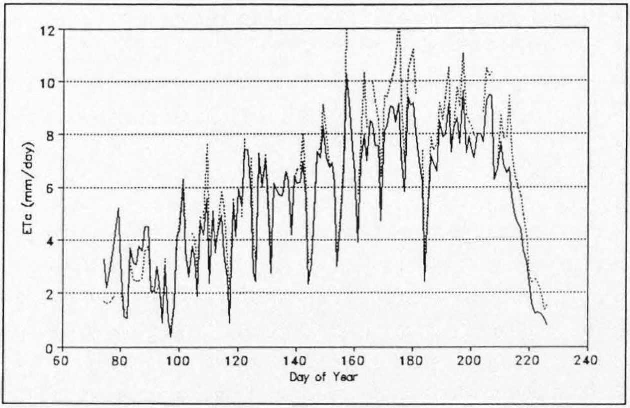

FIGURE 54. Measured (—) and Computed (···) Daily Evapotranspiration, Shuttleworth-Wallace (Winter Wheat, 1978).

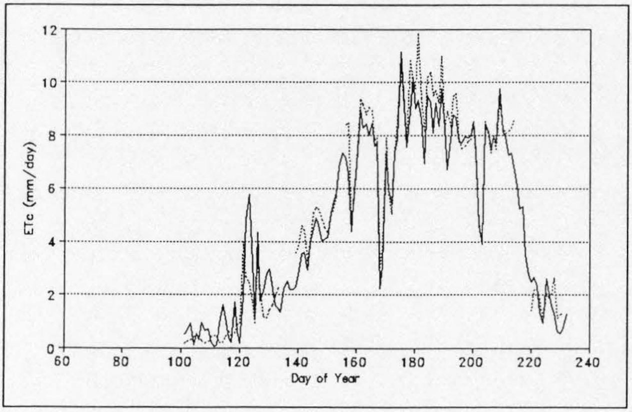

FIGURE 55. Measured (—) and Computed (···) Daily Evapotranspiration, Shuttleworth-Wallace (Spring Wheat, 1979).

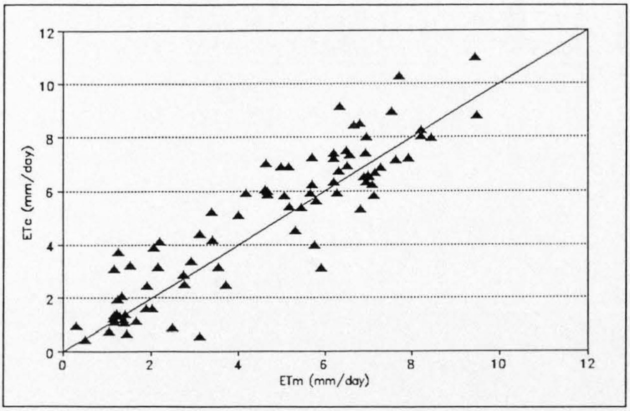

FIGURE 56. Computed versus Measured Daily Evapotranspiration, Shuttleworth-Wallace (Snap Beans, 1973).

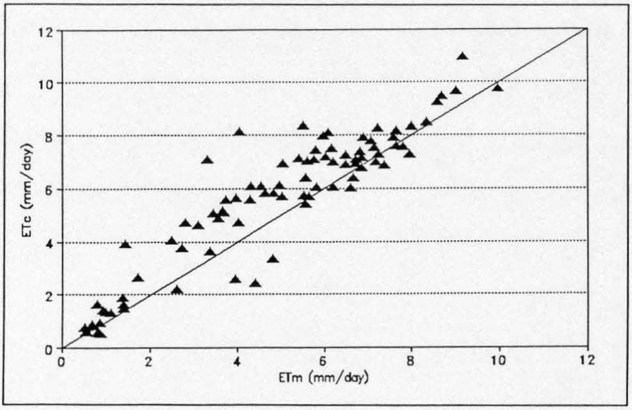

FIGURE 57. Computed versus Measured Daily Evapotranspiration, Shuttleworth-Wallace (Snap Beans, 1974).

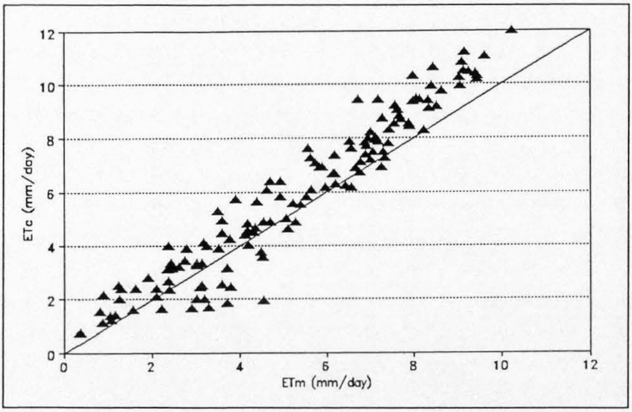

FIGURE 58. Computed versus Measured Daily Evapotranspiration, Shuttleworth-Wallace (Winter Wheat, 1978).

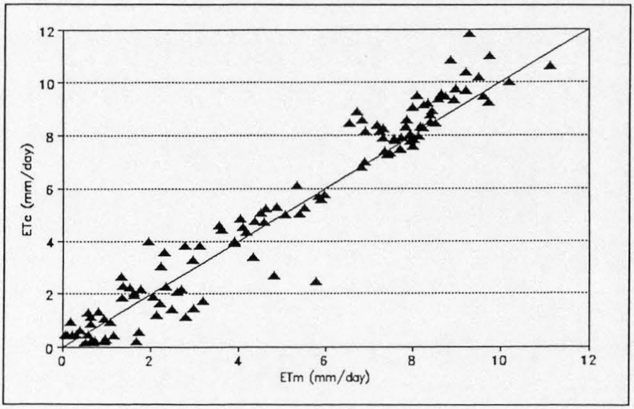

FIGURE 59. Computed versus Measured Daily Evapotranspiration, Shuttleworth-Wallace (Spring Wheat, 1979).

TABLE 15. Statistics for the Shuttleworth-Wallace Model (Basal).

Crop	N	ΣET_m (mm)	ΣET_c (mm)	$\Sigma ET_c/\Sigma ET_m$	RMSE (mm d^{-1})
Snap beans 1	43	173	191	1.10	1.08
Snap beans 2	48	198	234	1.18	1.35
Winter wheat	78	446	495	1.11	1.06
Spring wheat	75	342	362	1.06	0.76

Because the plant and soil resistances in the Shuttleworth-Wallace model were computed in exactly the same manner as for Penman-Monteith model I, the benefits of using a two-layer model instead of a single-layer model can be evaluated by comparing Figs. 36 through 39 to Figs. 52 through 55 and Tables 10 and 11 to Tables 14 and 15. Such a comparison indicates that the use of the two-layer model improved the estimates of evapotranspiration in the early season (less underestimation) but failed to remove the overestimation towards the end of the season. This strengthens the suspicion that the overestimation of evapotranspiration during ripening can be attributed entirely to an underestimation of plant resistance. Because the underestimation in the early season was removed, but the overestimation towards harvest persisted, the seasonal ratio of computed to measured evapotranspiration increased, whereas the RMSE decreased slightly.

Estimation of Input Variables

Energy Fluxes

Net Radiation. Daily surface albedos, back-calculated from the daily average data obtained at the USDA-ARS lysimeter site by rearranging the approach of Wright (1982), are shown in Figs. 60 through 64 for bare soil, snap beans, winter wheat and spring wheat.

Figure 60 shows that the albedo of a bare soil clearly is a function of its surface wetness and increases as the surface dries. The albedos of a fully wet and a fully dry soil were equal to 0.10 and 0.35 respectively.

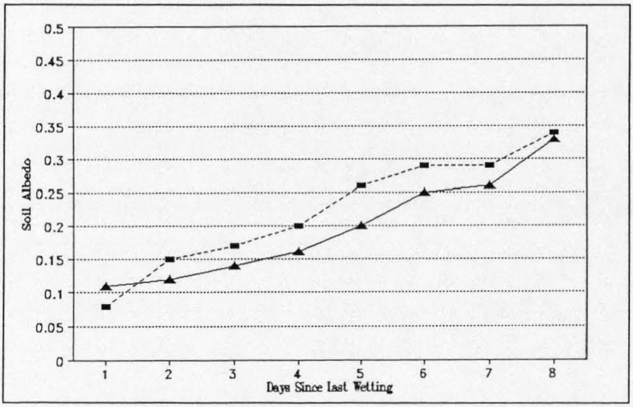

FIGURE 60. Computed Daily Albedo (Bare Soil, 1977), First Series (—) and Second Series (···).

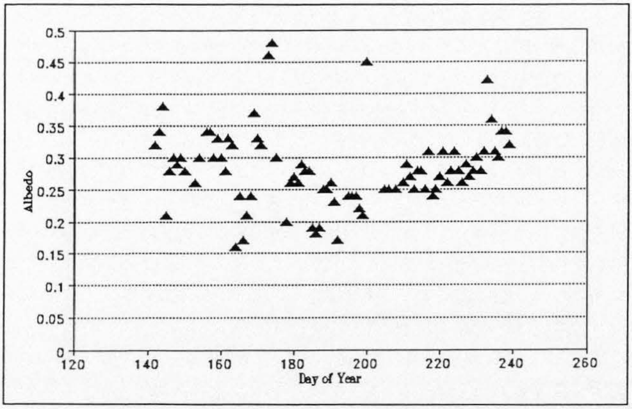

FIGURE 61. Computed Daily Albedo (Snap Beans, 1973).

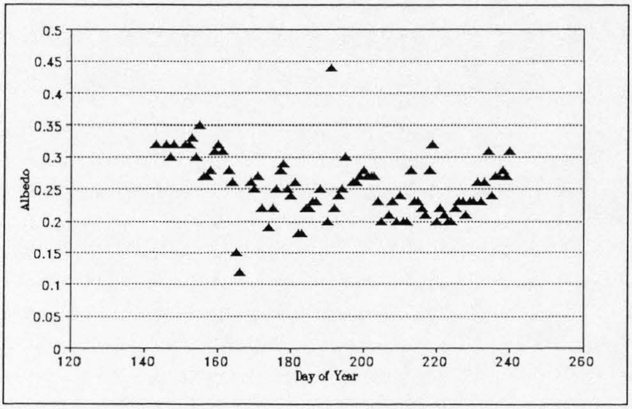

FIGURE 62. Computed Daily Albedo (Snap Beans, 1974).

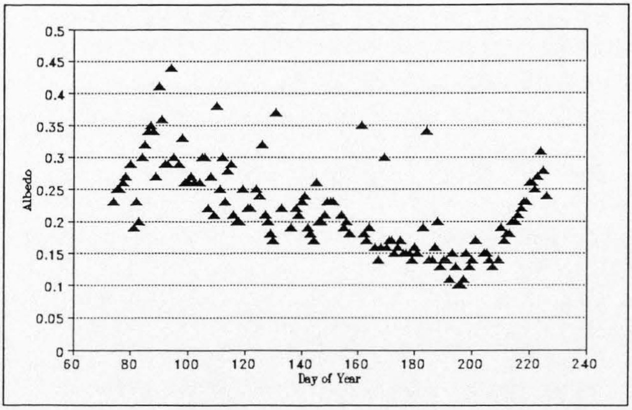

FIGURE 63. Computed Daily Albedo (Winter Wheat, 1978).

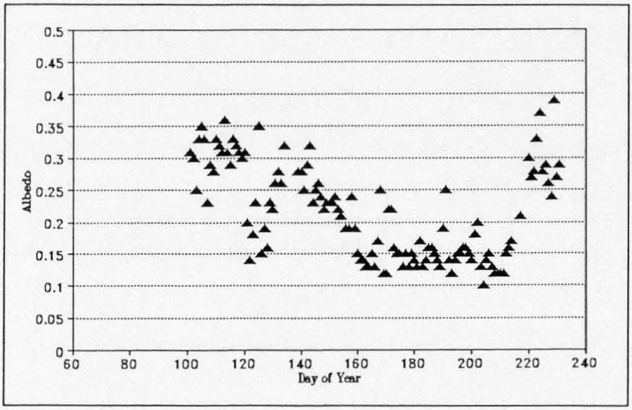

FIGURE 64. Computed Daily Albedo (Spring Wheat, 1979).

Figures 61 through 64 all show the same general trend: a large scatter in the beginning of the season, a minimum during full cover and an increase towards harvest. The large variations in the early growing season correspond to varying soil moisture conditions (low values for wet soil, high values for dry soil), whereas the increase towards harvest reflects the yellowing of the ripening crop. The latter effect is most pronounced in the case of wheat (1978 and 1979). The albedo of the fully developed bean crop in the 1973 growing season was slightly higher than the albedo of the crop in the 1974 season. This difference probably resulted from the fact that the 1973 crop was less dense and more bare soil remained exposed. Throughout the various growing seasons, a few exceptionally high albedos can be noted. These high values correspond to very cloudy, overcast days.

On the basis of Figs. 61 through 64, the following values for plant albedo at key growth stages (see Table 3) were selected: 0.25 at emergence, 0.23 at effective cover, 0.23 at the onset of ripening and 0.30 at harvest for beans and 0.25 at emergence, 0.15 at effective cover, 0.15 at the onset of ripening and 0.35 at harvest for wheat. Whenever R_s/R_{so} was less than 0.7, surface albedo was assumed to be 0.35, irrespective of percent cover. These values were inserted in the albedo model described in the previous chapter (Eqs. 112 through 114).

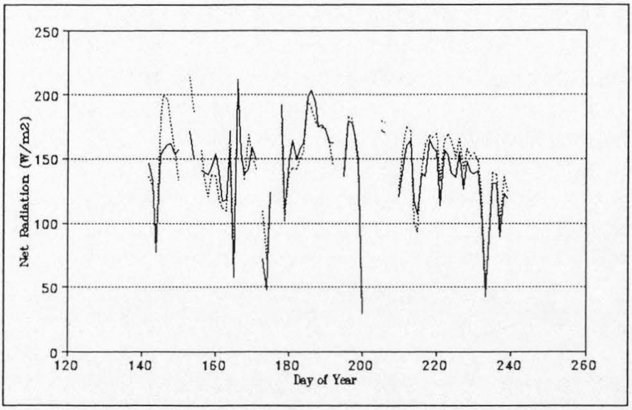

FIGURE 65. Measured (—) and Computed (···) Daily Net Radiation (Snap Beans, 1973).

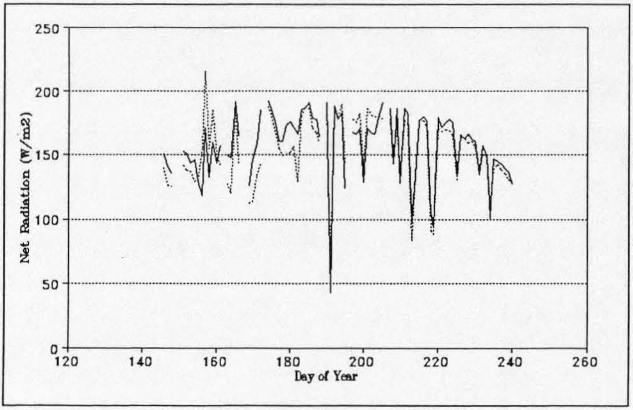

FIGURE 66. Measured (—) and Computed (···) Daily Net Radiation (Snap Beans, 1974).

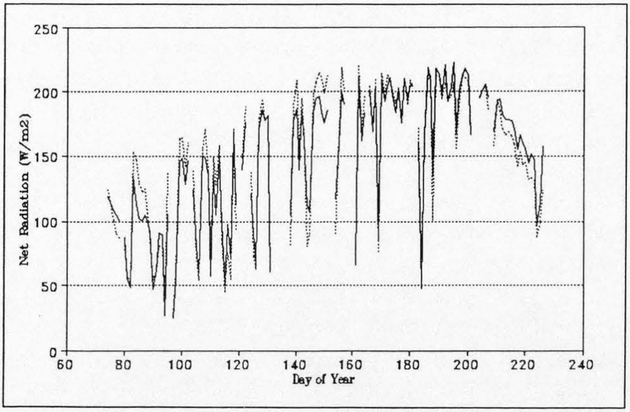

FIGURE 67. Measured (—) and Computed (···)
Daily Net Radiation (Winter Wheat, 1978).

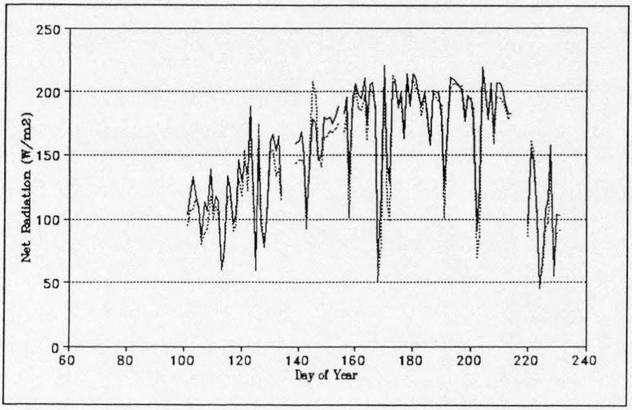

FIGURE 68. Measured (—) and Computed (···)
Daily Net Radiation (Spring Wheat, 1979).

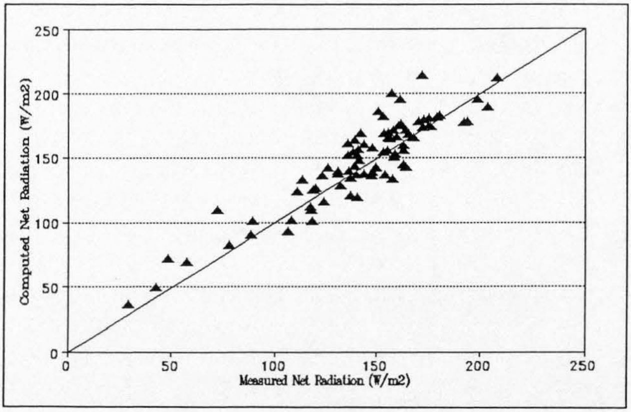

FIGURE 69. Computed versus Measured Daily Net Radiation (Snap Beans, 1973).

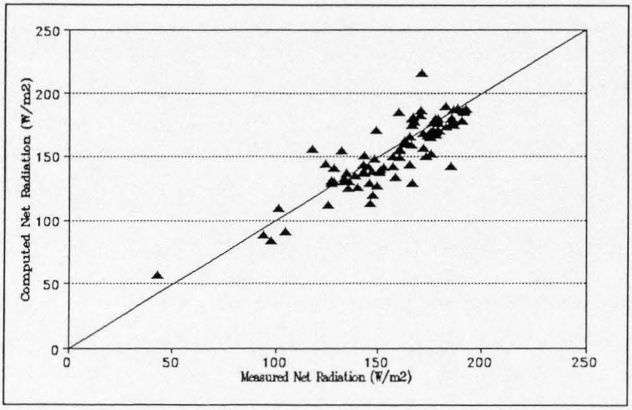

FIGURE 70. Computed versus Measured Daily Net Radiation (Snap Beans, 1974).

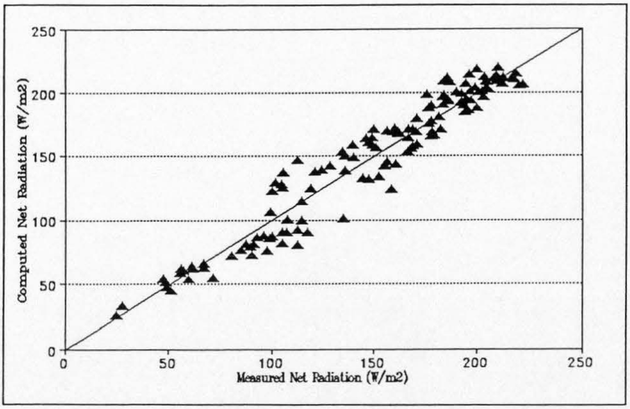

FIGURE 71. Computed versus Measured Daily Net Radiation (Winter Wheat, 1978).

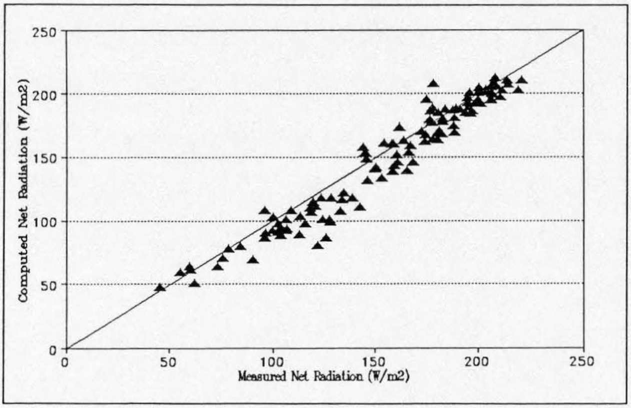

FIGURE 72. Computed versus Measured Daily Net Radiation (Spring Wheat, 1979).

A comparison of the resulting computed daily net radiation and the measured daily net radiation is shown in Figs. 65 through 72 for each of the four growing seasons. These figures show that the agreement is reasonable, though not excellent: the overall trend is correct, but errors of up to 25 percent in individual values can be observed. The RMSE was equal to 15 W m^{-2} for both years of beans and 13 W m^{-2} for both years of wheat.

Soil Heat Flux. The ratios of daily soil heat flux to daily net radiation (both measured at the USDA-ARS lysimeter site) are shown in Figs. 73 through 76. These ratios follow an expected trend, namely high with a lot of scatter for a bare soil and much lower for full cover conditions. The scatter in the early season is only weakly related to soil moisture content. In general, soil heat flux tends to be negative (i.e. upward) when the soil is very wet and positive (i.e. downward) when the surface is very dry, but many exceptions exist and trends are not very pronounced. In an attempt to remove some of the scatter, the ratio was recomputed using only data from daylight hours (defined as hours when the solar radiation is positive). This correction did not significantly improve the results: scatter remained significant and was still hard to explain on the basis of soil moisture only.

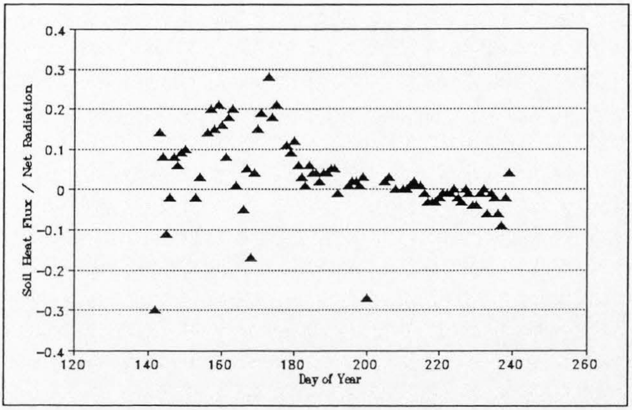

FIGURE 73. Daily Ratio of Soil Heat Flux to Net Radiation (Snap Beans, 1973).

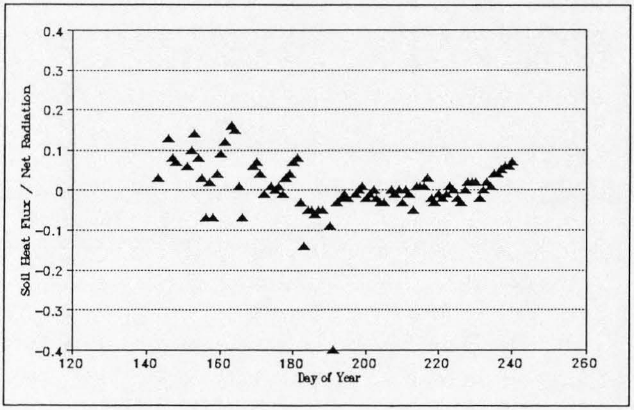

FIGURE 74. Daily Ratio of Soil Heat Flux to Net Radiation (Snap Beans, 1974).

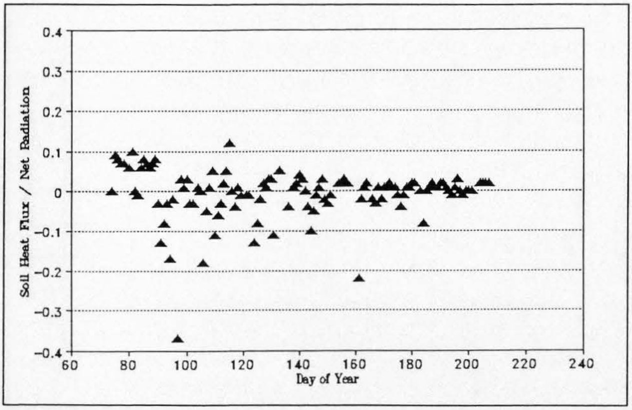

FIGURE 75. Daily Ratio of Soil Heat Flux to Net Radiation (Winter Wheat, 1978).

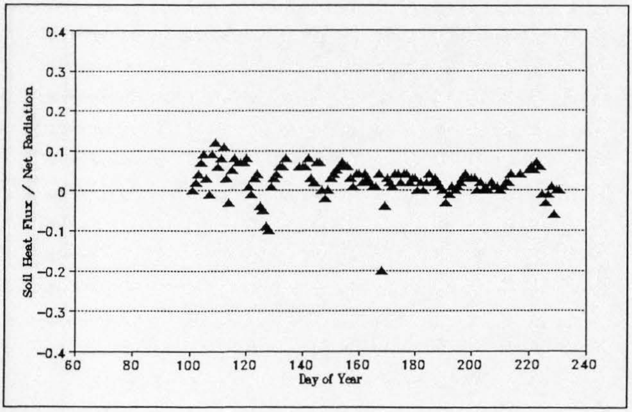

FIGURE 76. Daily Ratio of Soil Heat Flux to Net Radiation (Spring Wheat, 1979).

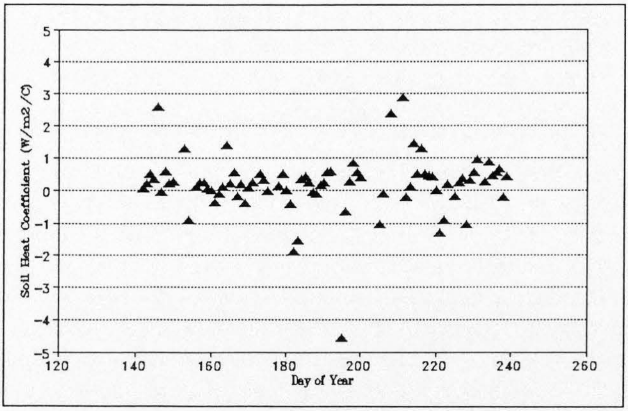

FIGURE 77. Daily Soil Heat Coefficient (Snap Beans, 1973).

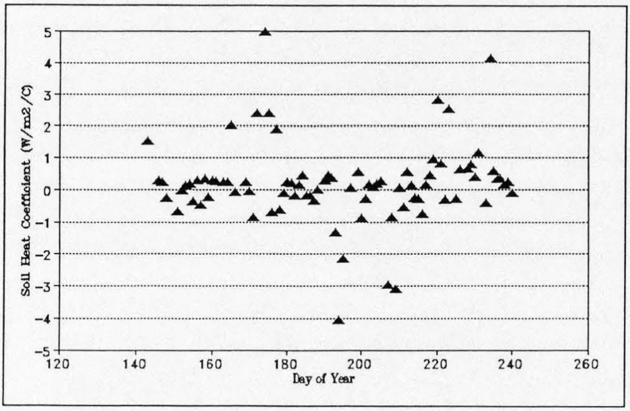

FIGURE 78. Daily Soil Heat Coefficient (Snap Beans, 1974).

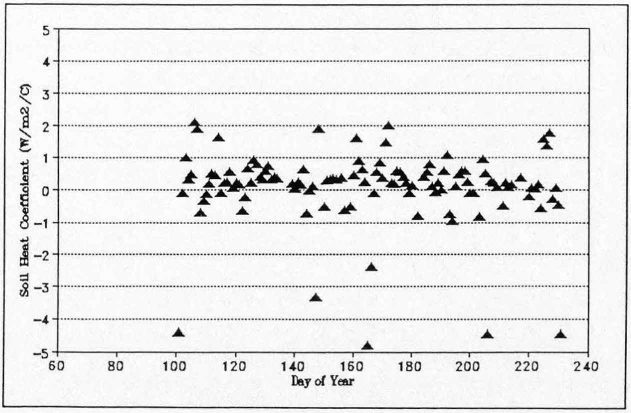

FIGURE 79. Daily Soil Heat Coefficient (Winter Wheat, 1978).

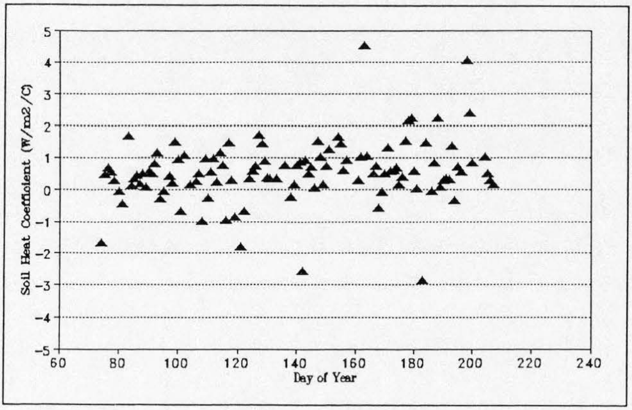

FIGURE 80. Daily Soil Heat Coefficient (Spring Wheat, 1979).

The back-calculation of the soil heat coefficient of Eq. 26 was not very successful either: the values obtained for the heat coefficient exhibited a wide range, including (physically impossible) negative values (see Figs. 77 through 80). Decreasing the number of days used in the calculation of T_p from three to two and even one did not improve the results, but rather made them worse.

The problems with the prediction of soil heat flux might, at least in part, have been caused by the fact that the measured values were obtained at a depth of 5 cm and were not corrected for flux variation in the upper 5 cm. Another factor that cannot be neglected is the spatial variability of soil heat flux, especially when the soil surface is only partially shaded by a row crop or only partially wetted by furrow irrigation. During the execution of the measurements, an attempt was made to locate the soil heat flux plate in a representative position, i.e. halfway between the row itself and the inter-row space.

In order to evaluate the impact of neglecting heat storage in the top 5 cm of the soil, the measured values of soil heat flux were compared to a second set of soil heat fluxes which had been tentatively corrected for heat storage on the basis of measurements of soil temperature at 5 cm depth, a rough estimate of the heat capacity of the top soil and very rough estimates of moisture content in the top soil (from gravimetric measurements executed in the surrounding field at about 5 day intervals). This comparison showed that for all four years of study, the seasonal RMSE was less than 1 W m^{-2}. In the early seasons, when soil heat fluxes were large, the inclusion of a correction for heat storage affected the magnitude of the soil heat flux, but did not affect its direction. Under full cover conditions, on the other hand, soil heat fluxes were much smaller and the correction for heat storage frequently altered the sign of the flux. Because the adjustments did not affect the direction of the soil heat flux during major parts of the growing season, the use of adjusted values of soil heat flux would not improve the results of either analysis descibed above. Even when using adjusted values of soil heat flux the sign of the daily ratio of soil heat flux to net radiation would remain only weakly related to soil wetness and the soil heat coefficient would continue to assume negative values.

Meteorological Observations

Temperature. The comparison of average daily air temperature at the lysimeter ($\Sigma T_{ai}/24$) and weather station ($(T_{min}+T_{max})/2$) is shown in Figs. 81 through 88 for the four years of record. These figures show that the agreement was remarkably good: to within 2 $\circ$C.

Vapor Pressure. Average daily vapor pressures at the lysimeter ($\Sigma e_{ai}/24$) and weather station (e_a at 8 am) are plotted in Figs. 89 through 96. The agreement between both sites was fairly good for wheat (1978 and 1979), but was a lot worse for beans (1973 and 1974). The differences are not unexpected since the readings at the weather station were all made in the early morning, whereas the values for the lysimeter represent daily averages. In addition, the measurements at the weather station are based upon wet and dry bulb temperatures, whereas those at the lysimeter site were made by means of a lithium chloride dew cell.

Vapor Pressure Deficit. The comparison of average daily vapor pressure deficit at the lysimeter ($\Sigma(e^o(T_{ai})-e_{ai})/24$) and weather station ($(e^o(T_{min})+e^o(T_{max}))/2-e_a$) is shown in Figs. 97 through 104 and reveals some clear trends. In the early part of the growing seasons, the agreement was reasonably good, but as the season progressed, the vapor pressure deficit at the lysimeter fell below that at the weather station. This could be the result of the development of an actively transpiring crop at the lysimeter, which progressively decreased the vapor pressure deficit.

Wind Speed. Average daily wind speeds at the lysimeter (u_2) and weather station ($u_{3.66}*(2/3.66)^{0.2}$) are compared in Figs. 105 through 112. Again, the general trend is clear and logical: a very good agreement early in the year, but as the crop at the lysimeter grew taller, the wind speed on this site dropped further below the wind speed measured at the grassed weather station.

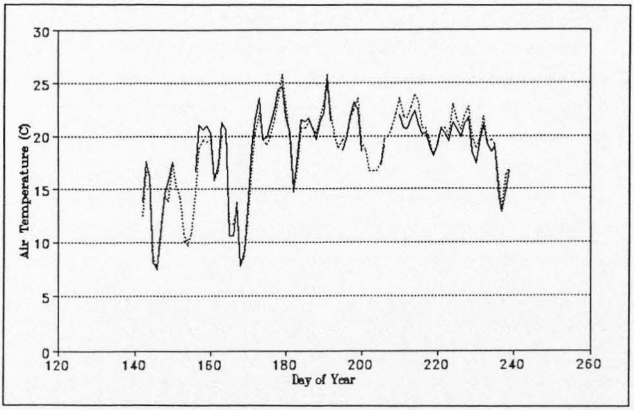

FIGURE 81. Temperature at Lysimeter (—) and Weather Station (···) (Snap Beans, 1973).

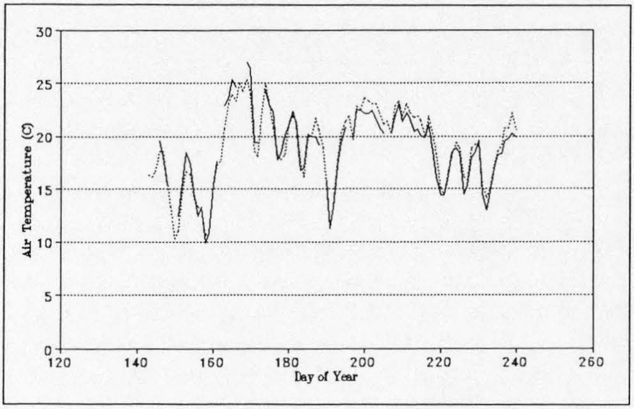

FIGURE 82. Temperature at Lysimeter (—) and Weather Station (···) (Snap Beans, 1974).

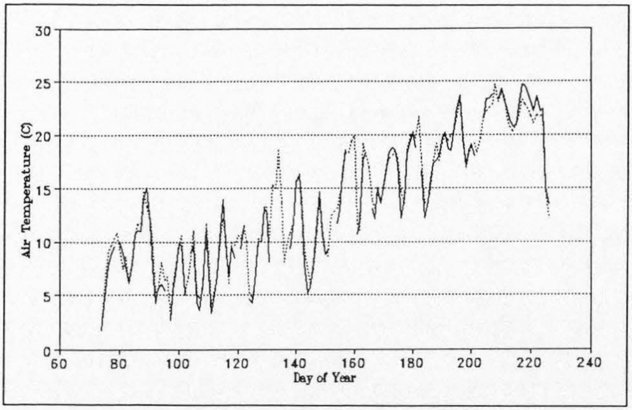

FIGURE 83. Temperature at Lysimeter (—) and Weather Station (···) (Winter Wheat, 1978).

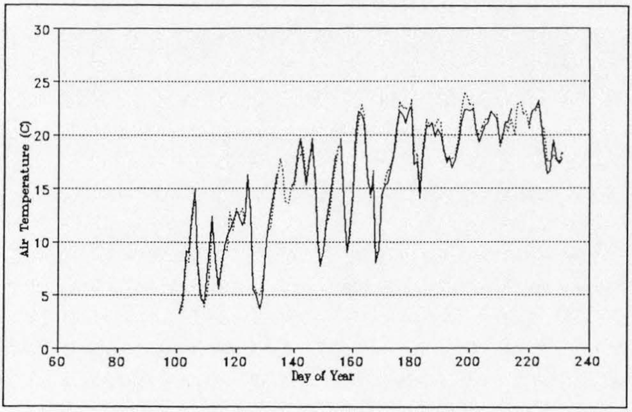

FIGURE 84. Temperature at Lysimeter (—) and Weather Station (···) (Spring Wheat, 1979).

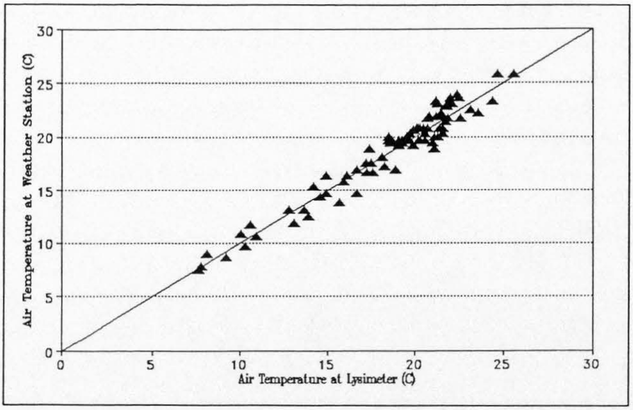

FIGURE 85. Temperature at Weather Station versus Temperature at Lysimeter (Snap Beans, 1973).

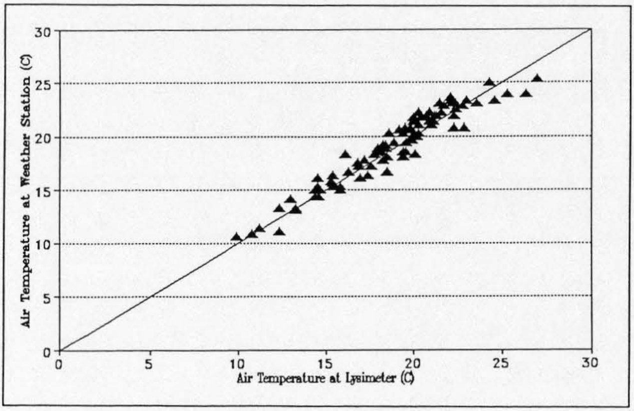

FIGURE 86. Temperature at Weather Station versus Temperature at Lysimeter (Snap Beans, 1974).

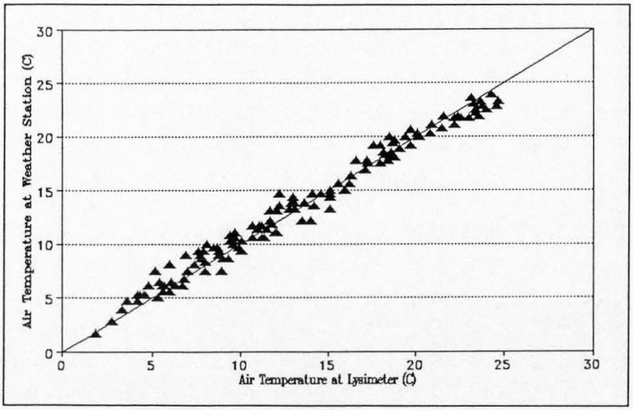

FIGURE 87. Temperature at Weather Station versus Temperature at Lysimeter (Winter Wheat, 1978).

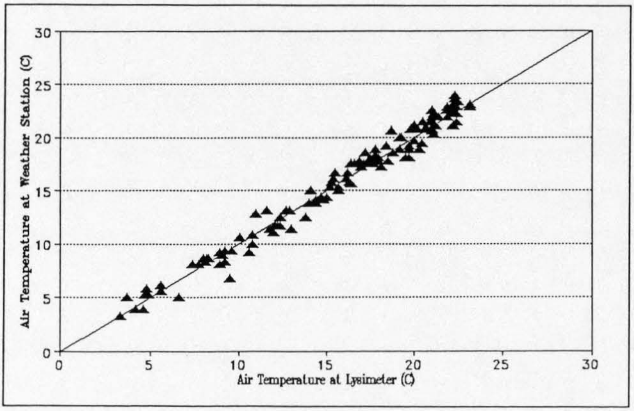

FIGURE 88. Temperature at Weather Station versus Temperature at Lysimeter (Spring Wheat, 1979).

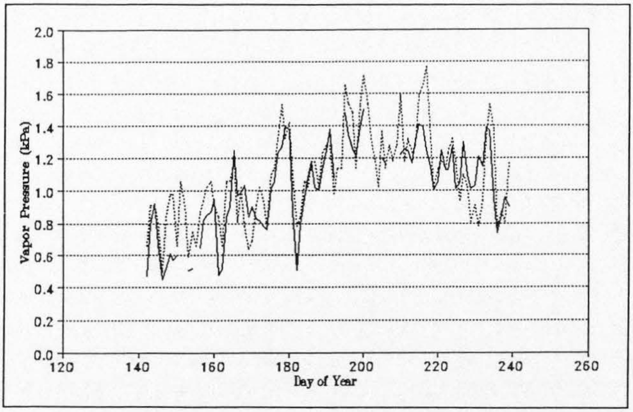

FIGURE 89. Vapor Pressure at Lysimeter (—) and Weather Station (···) (Snap Beans, 1973).

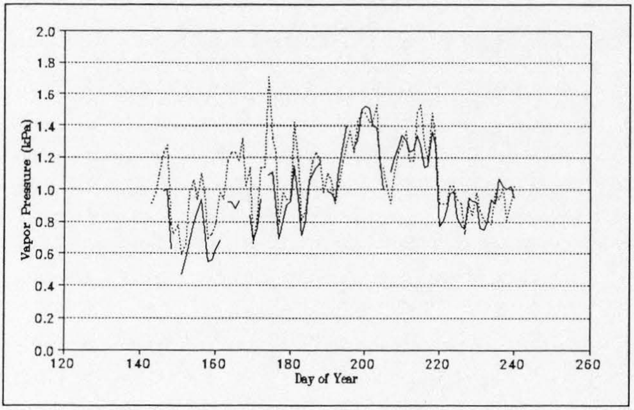

FIGURE 90. Vapor Pressure at Lysimeter (—) and Weather Station (···) (Snap Beans, 1974).

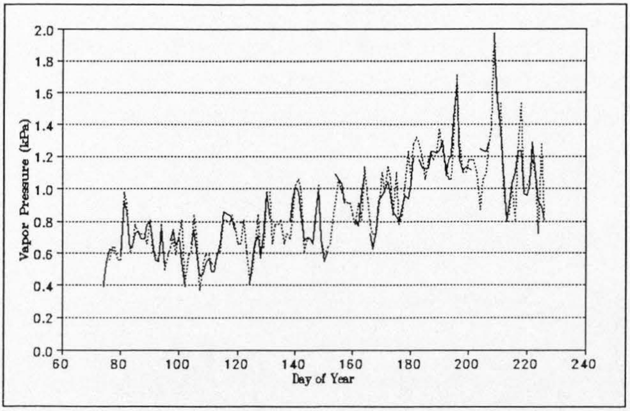

FIGURE 91. Vapor Pressure at Lysimeter (—) and Weather Station (···) (Winter Wheat, 1978).

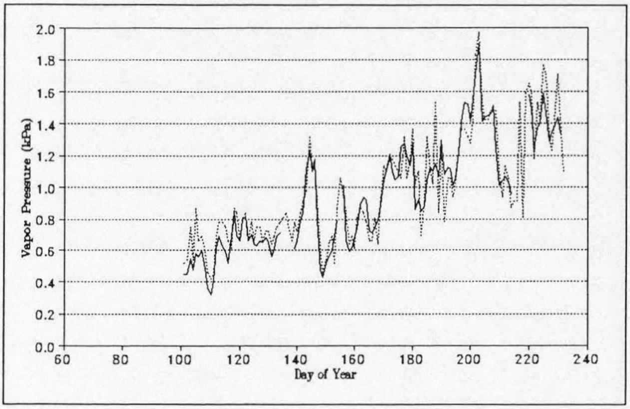

FIGURE 92. Vapor Pressure at Lysimeter (—) and Weather Station (···) (Spring Wheat, 1979).

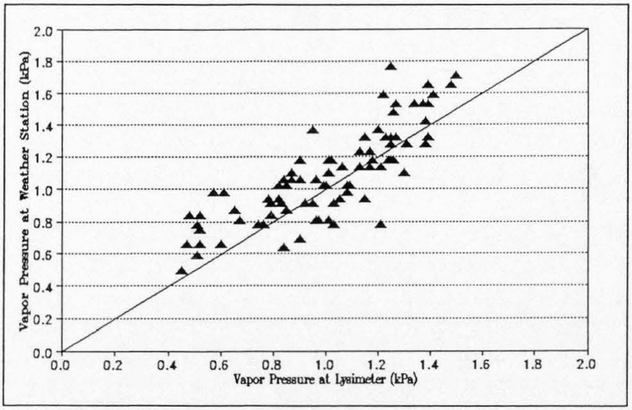

FIGURE 93. Vapor Pressure at Weather Station versus Vapor Pressure at Lysimeter (Snap Beans, 1973).

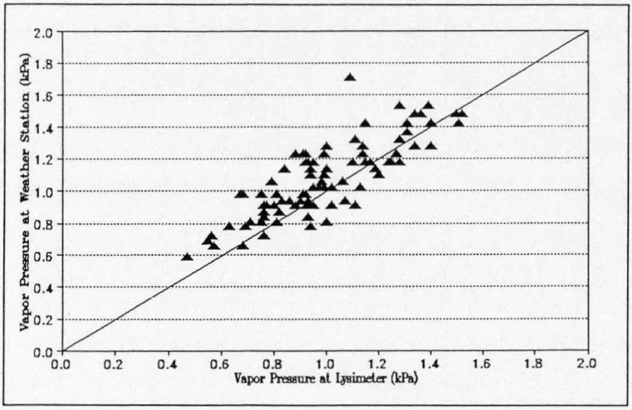

FIGURE 94. Vapor Pressure at Weather Station versus Vapor Pressure at Lysimeter (Snap Beans, 1974).

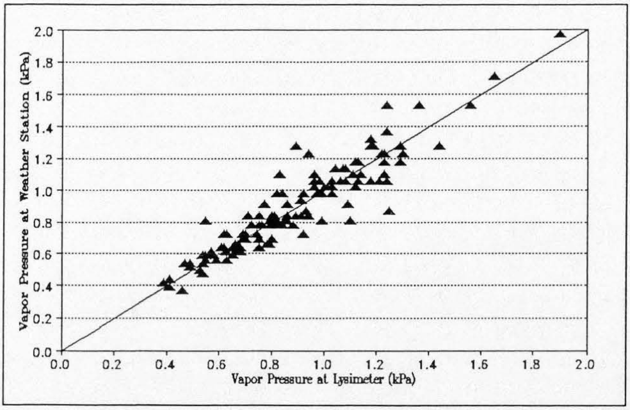

FIGURE 95. Vapor Pressure at Weather Station versus Vapor pressure at Lysimeter (Winter Wheat, 1978).

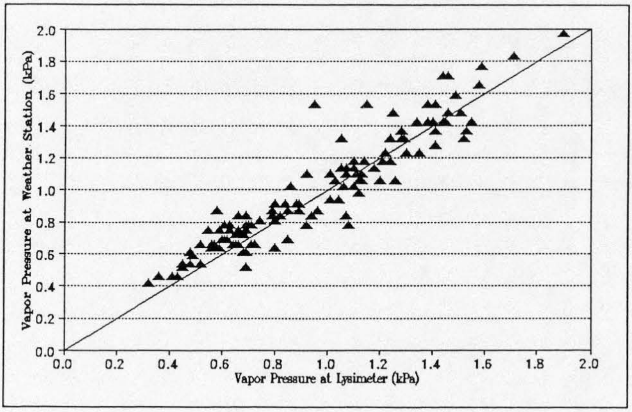

FIGURE 96. Vapor Pressure at Weather Station versus Vapor pressure at Lysimeter (Spring Wheat, 1979).

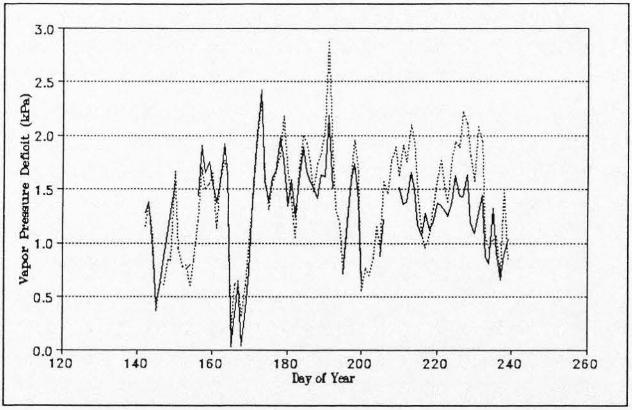

FIGURE 97. Vapor Pressure Deficit at Lysimeter (—) and Weather Station (···) (Snap Beans, 1973).

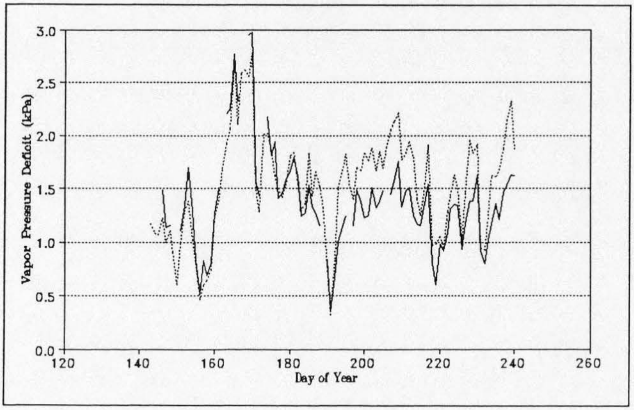

FIGURE 98. Vapor Pressure Deficit at Lysimeter (—) and Weather Station (···) (Snap Beans, 1974).

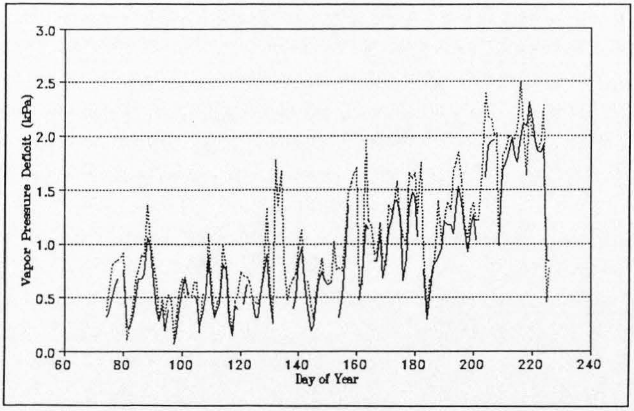

FIGURE 99. Vapor Pressure Deficit at Lysimeter (—) and Weather Station (···) (Winter Wheat, 1978).

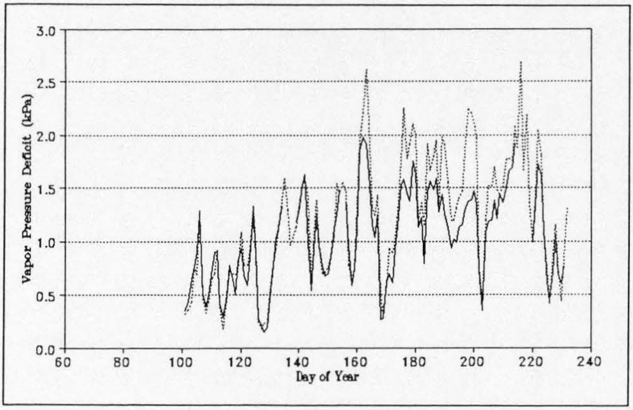

FIGURE 100. Vapor Pressure Deficit at Lysimeter (—) and Weather Station (···) (Spring Wheat, 1979).

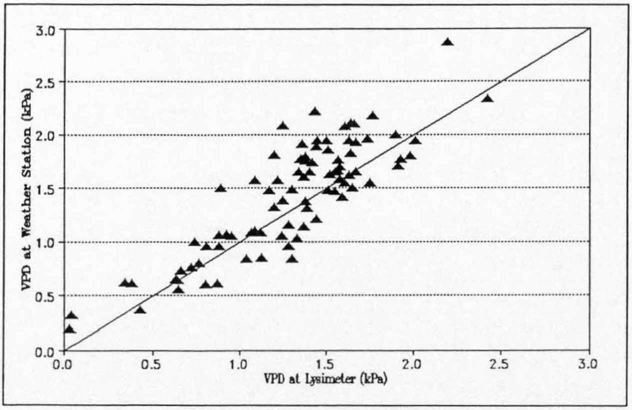

FIGURE 101. Vapor Pressure Deficit at Weather Station versus Vapor Pressure Deficit at Lysimeter (Snap Beans, 1973).

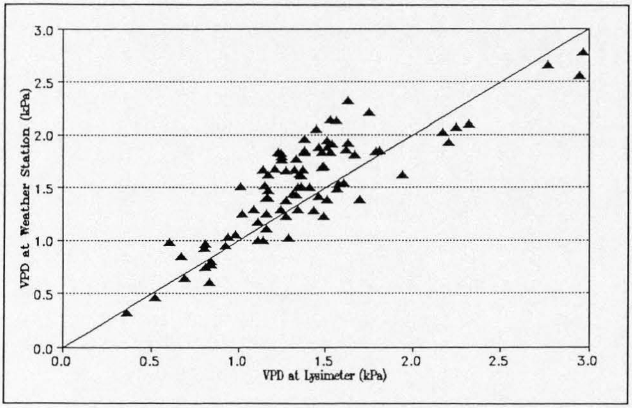

FIGURE 102. Vapor Pressure Deficit at Weather Station versus Vapor Pressure Deficit at Lysimeter (Snap Beans, 1974).

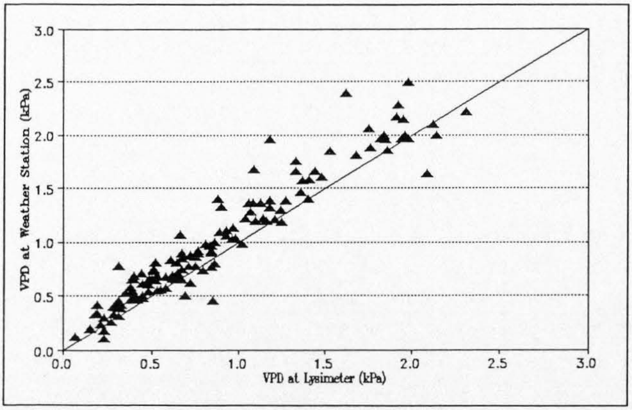

FIGURE 103. Vapor Pressure Deficit at Weather Station versus Vapor pressure Deficit at Lysimeter (Winter Wheat, 1978).

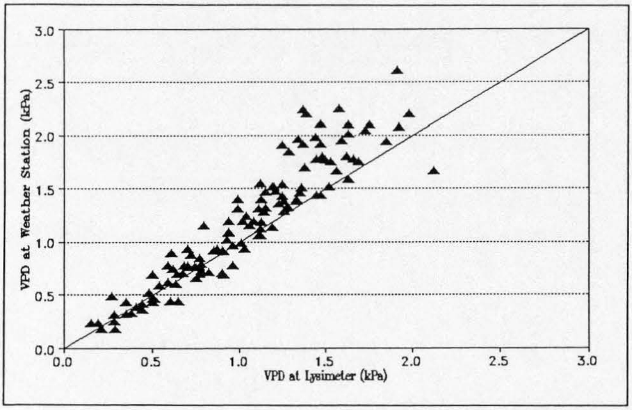

FIGURE 104. Vapor Pressure Deficit at Weather Station versus Vapor pressure Deficit at Lysimeter (Spring Wheat, 1979).

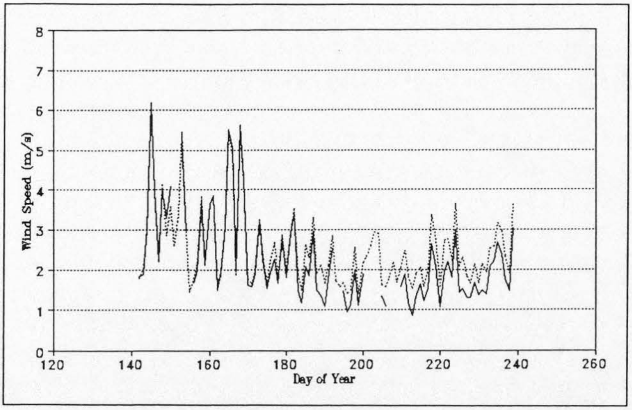

FIGURE 105. Wind Speed at Lysimeter (—) and Weather Station (···) (Snap Beans, 1973).

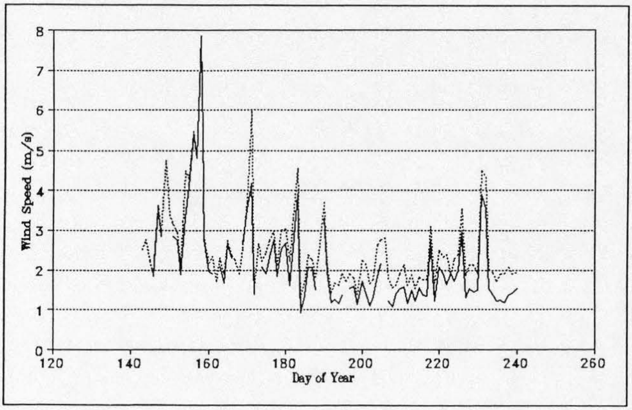

FIGURE 106. Wind Speed at Lysimeter (—) and Weather Station (···) (Snap Beans, 1974).

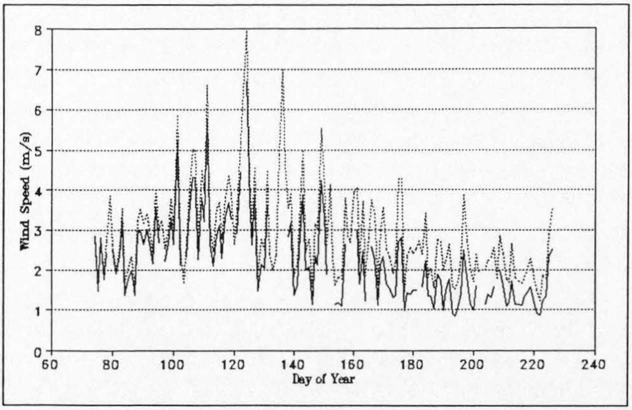

FIGURE 107. Wind Speed at Lysimeter (—) and Weather Station (···) (Winter Wheat, 1978).

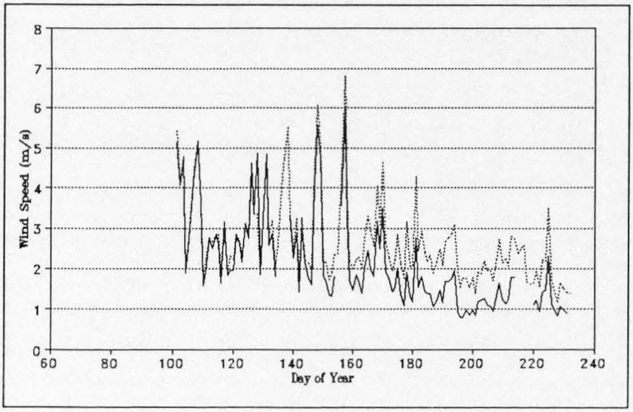

FIGURE 108. Wind Speed at Lysimeter (—) and Weather Station (···) (Spring Wheat, 1979).

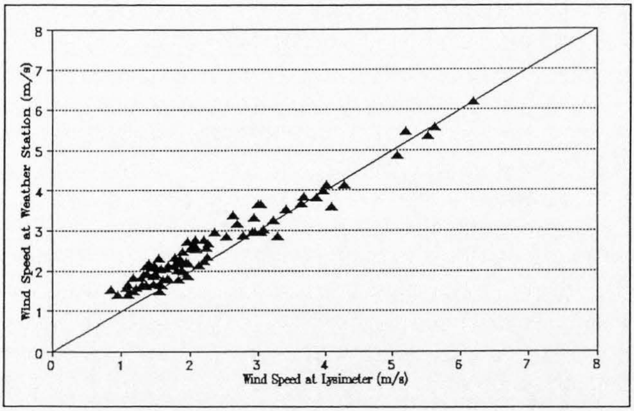

FIGURE 109. Wind Speed at Weather Station versus Wind Speed at Lysimeter (Snap Beans, 1973).

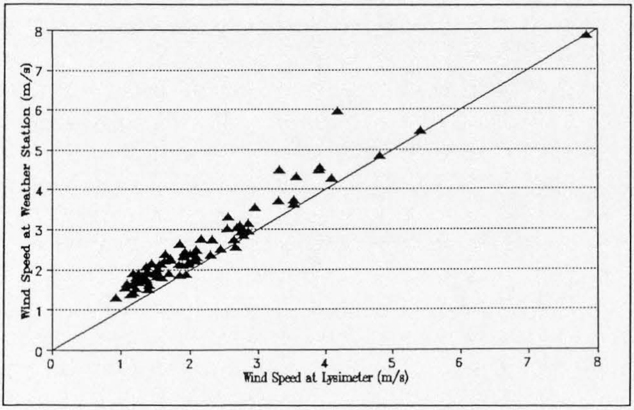

FIGURE 110. Wind Speed at Weather Station versus Wind Speed at Lysimeter (Snap Beans, 1974).

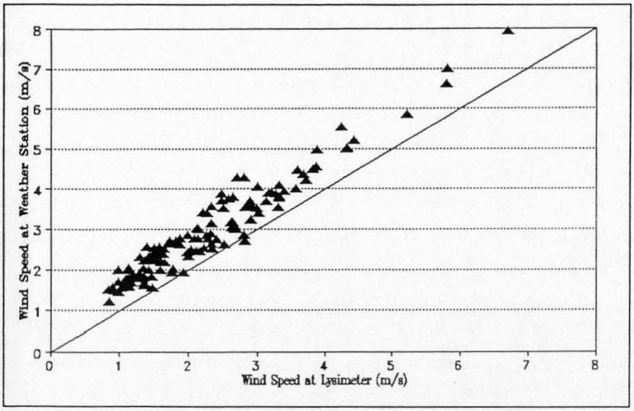

FIGURE 111. Wind Speed at Weather Station versus Wind Speed at Lysimeter (Winter Wheat, 1978).

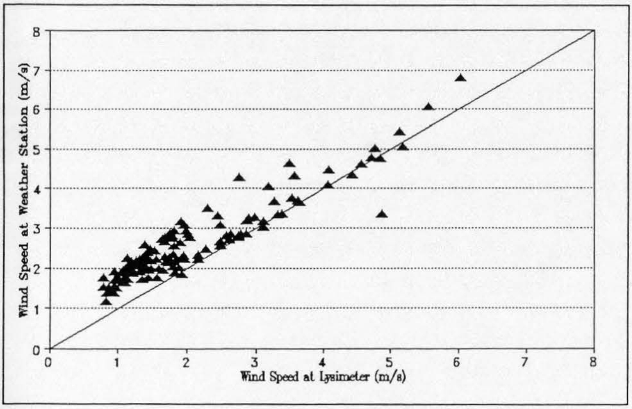

FIGURE 112. Wind Speed at Weather Station versus Wind Speed at Lysimeter (Spring Wheat, 1979).

Statistics. Table 16 lists the seasonal average ratio of the observations at the weather station to those at the lysimeter for the four years of study. Table 17 lists the seasonal RMSE for the same four years.

Table 16. Seasonal Average Ratio of the Observations at the Weather Station to those at the Lysimeter Site.

Crop	Temp (°C)	Vap Press (kPa)	Vap Press Def (kPa)	Wind Speed ($m\ s^{-1}$)
Snap Beans 1	1.01	1.07	1.10	1.13
Snap Beans 2	1.01	1.09	1.11	1.19
Winter Wheat	1.01	1.01	1.15	1.30
Spring Wheat	1.01	1.04	1.14	1.25

Table 17. Seasonal Average Root Mean Squared Error for the Observations at the Weather Station and at the Lysimeter Site.

Crop	Temp (°C)	Vap Press (kPa)	Vap Press Def (kPa)	Wind Speed ($m\ s^{-1}$)
Snap Beans 1	0.98	0.18	0.30	0.41
Snap Beans 2	0.99	0.16	0.31	0.49
Winter Wheat	0.92	0.10	0.21	0.73
Spring Wheat	0.81	0.13	0.26	0.68

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

The forelying work consisted of three major parts. The first part originally aimed at the development of simple expressions for the aerodynamic and surface resistance terms in the Penman-Monteith equation. This goal could not be achieved because of two reasons: first, the determination of aerodynamic resistance was rendered impossible because of problems with the measurements (the exact nature of which could not determined) and secondly, the back-calculation of surface resistance, which required prior knowledge of the aerodynamic resistance, turned out to be very sensitive to the assumptions underlying the estimates of aerodynamic resistance.

In the second part, two forms of the Penman-Monteith equation and one form of the Shuttleworth-Wallace model were implemented and their performance was compared to each other and to the traditional Kimberly-Penman approach. This analysis showed that:

(1) It was possible to fit a simple form of the Penman-Monteith equation to the measured data.

(2) Some forms of the Penman-Monteith equation (model II) allowed a better fit than the Kimberly-Penman approach.

(3) When identical expressions for surface resistance were used, a two-layer model (Shuttleworth-Wallace) provided

a slightly better fit to the data than did a single-layer model (Penman-Monteith model I).

Some important remarks need to be added to these observations. First, the resistance terms in the Penman-Monteith and Shuttleworth-Wallace model were not directly measured, but were rather estimated on the basis of a number of assumptions. These assumptions were often adjusted in order to improve the fit of the model to the data. As a result, the implementations described in this study did not really constitute an independent verification of these models. Secondly, the comparison between the resistance approach and the traditional approach was not entirely fair. The Kimberly-Penman model was implemented by means of the data from the U.S. Weather Service station, whereas both the Penman-Monteith and Shuttleworth-Wallace models were evaluated on the basis of the more extensive and higher quality data obtained at the USDA-ARS lysimeter site. The latter data set included a number of variables (net radiation, soil heat flux, crop height and leaf area index) which are usually not available to the practicing engineer.

In the third part, the possibility of estimating the net radiation and soil heat flux required for the implementation of a resistance model was investigated. In addition, a comparison was made between meteorological data obtained at a grassed weather station and those obtained above an agricultural crop. The results indicated that:

(1) It was difficult to obtain an accurate estimate of net radiation or soil heat flux for a partial canopy.

(2) Major differences existed between measurements of vapor pressure deficit and wind speed obtained above an agricultural crop and at a grassed weather station.

Conclusions

From the analysis described in this study, the author concludes that the benefit of using the Penman-Monteith equation instead of the traditional approach involving a reference equation and a crop coefficient is limited, in particular for the prediction of future crop evapotranspiration from a limited set of historical data obtained at a grassed weather station.

The main advantage of the Penman-Monteith equation lies in the fact that it is more physically based than the Penman equation. In practice, however, the necessity of using simplified, empirical expressions for the resistance terms reintroduces a large amount of unwanted empiricism. In addition, the use of the Penman-Monteith equation on a daily basis constitutes a major violation of the assumptions underlying the commonly used expressions for aerodynamic resistance. In the course of this study, it was shown that, in spite of this violation, it is still possible to develop a Penman-Monteith type model that provides an excellent fit to the data. However, in the process, a number of assumptions needed to be made that seem barely justifiable to the author. As a result, the originally physically based Penman-Monteith equation appears to have been reduced to a mere framework for fitting purposes. Because of the high number of variables involved, this framework proved to be very flexible, allowing for an excellent fit.

The Penman-Monteith equation may offer some advantages in applications of a descriptive nature, i.e. those applications in which the crop under study is physically present. In such situations, meteorological measurements can be executed at high frequency in the fully adjusted boundary layer above the crop and variables such as leaf area index, crop height and percent cover can be measured accurately. The use of the latter measurements allows the Penman-Monteith equation to reflect the specific characteristics of the crop under study, a flexibility which a standard crop coefficient cannot offer. An example of such a descriptive application is real time irrigation scheduling. One might wonder, however, if in such applications the need for an equation to compute crop evapotranspiration still exists. It would also be possible to simply measure crop evapotranspiration by means of a Bowen ratio or eddy correlation system. On the other hand, one could also argue that such systems are too fragile and too expensive to be left unattended for long periods of time or to be operated by unskilled labor. Even under those conditions, one could still estimate crop evapotranspiration from water balance computations based on neutron probe measurements of soil moisture content.

A second group of applications are those of a predictive nature. In these applications, one tries to predict the evapotranspiration from a crop that is expected to be grown in the future, but is not physically present at the time the prediction needs to be made. Examples are the planning of irrigation system operation and the design of new irrigation systems. Because the crop under study doesn't exist yet, no measurements can be executed, and one is forced to make do with historical observations from weather stations in the area. The use of the Penman-Monteith equation under such conditions would require the estimation of meteorological conditions above a cropped field from those observed at a weather station. In addition, the greater flexibility of the Penman-Monteith equation in comparison to the use of a crop coefficient would be partly lost because one would have to roughly estimate the anticipated crop height, leaf area index and crop cover. The use of standard curves for these variables, does not seem to offer any major advantage over the use of a single standard crop coefficient.

Recommendations

In view of all the previous considerations, the author does not recommend the use of the Penman-Monteith equation for the direct estimation of crop evapotranspiration in engineering applications. The author does recognize the limitations of the traditional approach to estimating crop evapotranspiration involving the use of a reference equation and a standard crop coefficient. The use of a single crop coefficient to represent any crop belonging to a given species ignores differences between cultivars, as well as differences in cultural practices and does not allow for an accurate prediction of the water use of a given cultivar under specific management conditions. However, the author does not believe that a solution to this problem is to be expected from a watered-down, semi-empirical version of the Penman-Monteith equation. A more promising alternative appears to be the two-step process described by Jagtap and Jones (1989a, 1989b). In a first step, these authors used a multitude of detailed research data to develop and validate a multi-layer crop-soil-atmosphere model. In a second step, they used this model to predict the variations in crop coefficients resulting from different climatological conditions and cultural practices. Jagtap and Jones (1989a, 1989b) applied their model to soybeans only. The author believes that it would be possible to develop similar models for all important agricultural crops. The development of such models would require a major, one-time research effort, to be executed under rigorously controlled experimental conditions. Upon completion of the development and validation of an accurate, multi-layer crop-soil-atmosphere model, this model could be used to develop a multitude of alternative sets of crop coefficients, each representing the behavior of a specific cultivar under particular management practices. These sets of crop coefficients could then be made available to the practicing engineers, for use with a traditional-style reference equation. This would relieve those practicing engineers of the burden of having to collect sufficient data to develop and operate an accurate multi-layer model themselves.

The development of such accurate multi-layer crop-soil-atmosphere models cannot be expected to take place without additional research efforts. During the past two decades, major progress has been made in the numerical simulation of plant-soil-atmosphere interactions, but many problem areas remain and require further attention. These problem areas include (but are not limited to) the measurement of individual leaf resistances, the modelling of stomatal behavior, the aerodynamic behavior of partial canopies and row crops and the modelling of within-canopy transport processes. Further study of these areas will hopefully lead to the development more accurate techniques for the estimation of evapotranspiration under either research conditions (through more accurate multi-layer models) or field conditions (through more versatile crop coefficients).

REFERENCES

Abtew, W., Gregory, J.M. and Borelli, J. 1989. "Wind Profile: Estimation of Displacement Height and Aerodynamic Roughness", Transactions ASAE, 32:521-527.

Allen, R.G. 1986. "A Penman for All Seasons", Journal of Irrigation and Drainage Engineering, ASCE, 112:348-368.

Allen, R.G., Jensen, M.E., Wright J.L. and Burman, R.D. 1989. "Operational Estimates of Reference Evapotranspiration", Agronomy Journal, 81:650-662.

Arkin, G.F. and Perrier, E.R. 1974. "Vorticular Air Flow within an Open Row Crop Canopy", Agricultural Meteorology, 13:359-374.

Azevedo, P.V. and Verma, S.B. 1986. "Aerodynamic Characteristics of Grain Sorghum", Agricultural and Forest Meteorology, 38:193-204.

Bailey, W.G. and Davies, J.A. 1980. "The Effect of Uncertainty in Aerodynamic Resistance on Evaporation Estimates from the Combination Model", Boundary-Layer Meteorology, 20:187-199.

Benoit, 1977. "On the Integral of the Surface Layer Profile-Gradient Functions", Journal of Applied Meteorology, 16:859-860.

Black, T.A., Tanner, C.B. and Gardner, W.R. 1970. "Evapotranspiration from a Snap Bean Crop", Agronomy Journal, 62:66-69.

Blaney, H.F. and Criddle, W.D. 1950. "Determining Water Requirements in Irrigated Areas from Climatological Data", USDA-SCS, SCS-TP96.

Brown, K.W. and Rosenberg, N.J. 1973. "A Resistance Model to Predict Evapotranspiration and its Application to a Sugar Beet Field", Agronomy Journal, 65:341-347.

Brun, L.J., Kanemasu, E.T. and Powers, W.L. 1972. "Evapotranspiration from Soybean and Sorghum Fields", Agronomy Journal, 64:145-148.

Brun, L.J., Kanemasu, E.T. and Powers, W.L. 1973. "Estimating Transpiration Resistance", Agronomy Journal, 65:326-328.

Brutsaert, W. 1975a. "Comments on Surface Roughness Parameters and the Height of Dense Vegetation", Journal of the Meteorological Society of Japan, 53:96-97.

Brutsaert, W. 1975b. "The Roughness Length for Water Vapor, Sensible Heat and Other Scalars", Journal of the Atmospheric Sciences, 32:2028-2031.

Brutsaert, W. 1979. "Heat and Mass Transfer to and from Surfaces with Dense Vegetation or Similar Permeable Roughness", Boundary-Layer Meteorology, 16:365-388.

Brutsaert, W. 1982. "Evaporation into the Atmosphere", R. Deidel Publishing Company, Dordrecht, Holland.

Burman, R.D., Wright, J.L. and Jensen, M.E. 1975. "Changes in Climate and Estimated Evaporation Across a Large Irrigated Area in Idaho", Transactions ASAE, 18:1089-1093.

Burman, R.D., Jensen, M.E. and Allen, R.G. 1987. "Thermodynamic Factors in Evapotranspiration", in "Irrigation Systems for the 21st Century", James, L.G. and English, M.J., eds., ASAE, St. Joseph, Michigan.

Businger, J.A. 1956. "Some Remarks on Penman's Equations for the Evapotranspiration", Netherlands Journal of Agricultural Science, 4:77-80.

Camillo, P.J. and Gurney, R.J. 1986. "A Resistance Parameter for Bare-Soil Evaporation Models", Soil Science, 141:95-105.

Chamberlain, A.C. 1966. "Transport of Gases to and from Grass and Grass-like Surfaces", Proceedings of the Royal Society A, 290:236-259.

Chen, J. 1984. "Uncoupled Multi-Layer Model for the Transfer of Sensible and Latent Heat Flux Densities from Vegetation", Boundary-Layer Meteorology, 28:213-225.

Chen, J. 1985. "A Graphical Extrapolation Method to Determine Canopy Resistance from Measured Temperature and Humidity Profiles above a Crop Canopy", Agricultural and Forest Meteorology, 33:291-297.

Choudhury, B.J. and Monteith, J.L. 1988. "A Four-Layer Model for the Heat Budget of Homogenous Land Surfaces", Quarterly Journal of the Royal Meteorological Society, 114:373-398.

Covey, W. 1963. "A Method for the Computation of Logarithmic Wind Profile Parameters and their Standard Errors", in "The Energy Budget at the Earth's Surface", USDA-ARS Production Research Report No 72, Part II, Washington, D.C..

Cowan, I.R. 1968. "Mass, Heat and Momentum Exchange Between Stands of Plants and their Atmospheric Environment", Quarterly Journal of the Royal Meteorological Society, 94:523-544.

Doorenbos, J. and Pruitt, W.O. 1977. "Guidelines for Predicting Crop Water Requirements", Irrigation and Drainage Paper No 24, 2nd Ed., FAO, Rome.

Dyer, A.J. 1974. "A Review of Flux-Profile Relationships", Boundary-Layer Meteorology, 7:363-372.

Endrodi, G. and Rijtema, P.E. 1969. "Calculation of Evapotranspiration from Potatoes", Netherlands Journal of Agricultural Science, 17:283-299.

Feddes, R.A. 1971. "Water, Heat and Crop Growth", Mededelingen Landbouwhogeschool Wageningen, 71-12, The Netherlands.

Fuchs, M. and Tanner, C.B. 1967. "Evaporation from a Drying Soil", Journal of Applied Meteorology, 6:852-857.

Gates, D.M. 1980. "Biophysical Ecology", Springer-Verlag, New York.

Garratt, J.R. and Hicks, B.B. 1973. "Momentum, Heat and Vapour Transfer to and from Natural and Artificial Surfaces", Quarterly Journal of the Royal Meteorological Society, 99:680-687.

Goudriaan, J. and Waggoner, P.E. 1972. "Simulating both Aerial Microclimate and Soil Temperature from Observations above the Foliar Canopy", Netherlands Journal of Agricultural Science, 20:104-124.

Grant, D.R. 1975. "Comparison of Evaporation from Barley with Penman Estimates", Agricultural Meteorology, 15:49-60.

Hargreaves, G.H. 1975. "Moisture Availability and Crop Production", Transactions ASAE, 18:980-984.

Harrison, L.P. 1963. "Fundamental Concepts and Definitions relating to Humidity", in "Humidity and Moisture", A. Wexler, ed., Vol. 3, Reinhold Publishing Company, New York.

Hatfield, J.L. 1989. "Aerodynamic Properties of Partial Canopies", Agricultural and Forest Meteorology, 46:15-22.

Heilman, J.L. and Kanemasu, E.T. 1976. "An Evaluation of a Resistance Form of the Energy Balance to Estimate Evapotranspiration", Agronomy Journal, 68:607-611.

Hipps, L.E. 1989. "The Infrared Emissivities of Soil and Artemisia tridentata and Subsequent Temperature Corrections in a Shrub-Steppe Ecosystem", Remote Sensing of the Environment, 27:337-342.

Huband, N.D.S. and Monteith, J.L. 1986. "Radiative Surface Temperature and Energy Balance of a Wheat Canopy, I. Comparison of Radiative and Aerodynamic Canopy Temperature", Boundary-Layer Meteorology, 36:1-17.

Idso, S.B., Allen, S.G. and Choudhury, B.J. 1988. "Problems with Porometry: Measuring Stomatal Conductances of Potentially Transpiring Plants", Agricultural and Forest Meteorology, 43:49-58.

Jacobs, A.F.G. and Van Boxel, J.H. 1988. "Changes of the Displacement Height and Roughness Length of Maize during a Growing Season", Agricultural and Forest Meteorology, 42:53-62.

Jagtap, S.S. and Jones, J.W. 1989a. "Evapotranspiration Model for Developing Crops", Transactions ASAE, 32:1342-1350.

Jagtap, S.S. and Jones, J.W. 1989b. "Stability of Crop Coefficients under Different Climate and Irrigation Management Practices", Irrigation Science, 10:231-244.

Jensen, M.E., Burman, R.D. and Allen, R.G. 1990. "Evapotranspiration and Irrigation Water Requirements", Manuals and Reports on Engineering Practice No 70, ASCE.

Jensen, M.E. and Haise, H.R. 1963. "Estimating Evapotranspiration from Solar Radiation", Journal of the Irrigation and Drainage Division, ASCE, 89:15-41.

Jensen, M.E., Robb, D.C.N. and Franzoy, C.E. 1970. "Scheduling Irrigations using Climate-Crop-Soil Data", Journal of the Irrigation and Drainage Division, ASCE, 96:25-28.

Jones, H.G. 1983. "Plants and Microclimate", Cambridge University Press, New York.

Jordan, W.R. and Ritchie, J.T. 1971. "Influence of Soil Water Stress on Evaporation, Root Absorption and Internal Water Status of Cotton", Plant Physiology, 48:783-788.

Katerji, N. and Perrier, A. 1985. "Determination de la Resistance Globale d'un Couvert Vegetal a la Diffusion de Vapeur d'Eau et de ses Differentes Composantes", Agricultural and Forest Meteorology, 34:105-120.

Kohsiek, W. 1981. "A Rapid-Circulation Evaporation Chamber for Measuring Bulk Stomatal Resistance", Journal of Applied Meteorology, 20:42-52.

Kondo, J. 1971. "Relationship between the Roughness Coefficient and other Aerodynamic Parameters", Journal of the Meteorological Society of Japan, 50:487-488.

Kondo, J. and Kawanaka, A. 1986. "Numerical Study on the Bulk Heat Transfer Coefficient for a Variety of Vegetation Types and Densities", Boundary-Layer Meteorology, 37:285-296.

Lafleur, P.M. and Rouse, W.R. 1990. "Application of an Energy Combination Model for Evaporation from Sparse Canopies", Agricultural and Forest Meteorology, 49:135-153.

Legg, B.J., Long, I.F. and Zemroch, P.J. 1981. "Aerodynamic Properties of Field Bean and Potato Crops", Agricultural Meteorology, 23:21-43.

Lettau, H. 1957. "Computation of Richardson Numbers, Classification of Wind Profiles and Determination of Roughness Parameters", in "Exploring the Atmosphere's First Mile", H. Lettau and B. Davidson, eds., Vol. 1, Pergamon Press, New York.

Lettau, H. 1969. "Note on Aerodynamic Roughness-Parameter Estimation on the Basis of Roughness-Element Description", Journal of Applied Meteorology, 8:828-832.

Lhomme, J.P. 1988a. "Extension of Penman's Formulae to Multi-Layer Models", Boundary-Layer Meteorology, 42:281-291.

Lhomme, J.P. 1988b. "A Generalized Combination Equation Derived from a Multi-Layer Micrometeorological Model", Boundary-Layer Meteorology, 45:103-115.

Massman, W. 1987a. "A Comparative Study of some Mathematical Models of the Mean Wind Structure and Aerodynamic Drag of Plant Canopies", Boundary-Layer Meteorology, 40:179-197.

Massman, W. 1987b. "Heat transfer to and from Vegetated Surfaces: an Analytical Method for the Bulk Exchange Coefficients", Boundary-Layer Meteorology, 40:269-281.

Massman, W.J. and Van Dijken, A. 1989. "Water Vapor Transfer from a Vegetated Surface: a Numerical Study of Bulk Transfer Coefficients and Canopy Resistances", Boundary- Layer Meteorology, 49:295-307.

McNaughton, K.G. and Jarvis P.G., 1984. "Using the Penman-Monteith Equation Predictively", Agricultural Water Management, 8:263-278.

Monteith, J.L. 1963. "Gas Exchange in Plant Communities", in "Environmental Control of Plant Growth", L.T. Evans, ed., Academic Press, New York.

Monteith, J.L. 1965. "Evaporation and Environment", Symposia of the Society for Experimental Biology, 19:205-234.

Monteith, J.L. 1973. "Principles of Environmental Physics", Edward Arnold, London.

Monteith, J.L. 1977. "Resistance of a Partially Wet Canopy: Whose Equation Fails ?", Boundary Layer Meteorology, 12:379-383.

Monteith, J.L. 1981. "Evaporation and Surface Temperature", Quarterly Journal of the Royal Meteorological Society, 107:1-27.

Monteith, J.L., Szeicz, G. and Waggoner, P.E. 1965. "The Measurement and Control of Stomatal Resistance in the Field", Journal of Applied Ecology, 1:345-355.

Monteith, J.L. and Unsworth, M.H. 1990. "Principles of Environmental Physics", 2nd ed., Edward Arnold, London.

Munro, D.S. and Oke, T.R. 1973. "Estimating Wind Profile Parameters for Tall Dense Crops", Agricultural Meteorology, 11:223-228.

Munro, D.S. and Oke, T.R. 1975. "Aerodynamic Boundary Layer Adjustment over a Crop in Neutral Stability, Boundary-Layer Meteorology, 9:53-61.

Nkemdirim, L.C. 1976. "Crop Development and Water Loss - A Case Study over a Potato Crop", Agricultural Meteorology, 16:371-388.

Oke, T.R. 1977. "Boundary Layer Climates", John Wiley and Sons, New York.

Owen, P.R. and Thomson, W.R. 1963. "Heat Transfer across Rough Surfaces", Journal of Fluid Mechanics, 15:321-334.

Paulson, 1970. "The Mathematical Representation of Wind Speed and Temperature Profiles in the Unstable Atmospheric Surface Layer", Journal of Applied Meteorology, 9:857-861.

Penman, H.L. 1948. "Natural Evaporation from Open Water, Bare Soil and Grass", Proceedings of the Royal Society A, 193:120-145.

Penman, H.L. 1952. "The Physical Bases of Irrigation Control", Report of the 13th International Horticultural Congress, London, 2:913-924.

Penman, H.L. 1961. "Weather, Plant and Soil Factors in Hydrology", Weather, 16:207-219.

Penman, H.L. 1963. "Vegetation and Hydrology", Technical Communication No 53, Commonwealth Bureau of Soils, Harpenden, England.

Penman, H.L. and Schofield, R.K. 1951. "Some Physical Aspects of Assimilation and Transpiration", Symposia of the Society for Experimental Biology, 5:115-129.

Perrier, E.R., Millington, R.J., Peters, D.B. and Luxmoore, R.J. 1970. "Wind Structure Above and Within a Soybean Canopy", Agronomy Journal, 62:615-618.

Perrier, E.R., Robertson, J.M., Millington, R.J. and Peters, D.B. 1972. "Spatial and Temporal Variation of Wind Above and Within a Soybean Canopy", Agricultural Meteorology, 10:421-442.

Philip, J.R. 1964. "Sources and Transfer Processes in the Air Layers Occupied by Vegetation", Journal of Applied Meteorology, 3:390-395.

Philip, J.R. 1966. "Plant Water Relations: Some Physical Aspects", Annual Review of Plant Physiology, 17:245-268.

Priestley, C.H.B. and Taylor, R.J. 1972. "On the Assessment of Surface Heat Flux and Evaporation using Large Scale Parameters", Monthly Weather Review, 100:81-92.

Pruitt, W.O, Morgan, D.L. and Lourence, F.J. 1973. "Momentum and Mass Transfers in the Surface Boundary Layer", Quarterly Journal of the Royal Meteorological Society, 99:370-386.

Rijtema, P.E. 1965. "An Analysis of Actual Evapotranspiration", Agricultural Research Report No 659, Institute for Land and Water Management Research, Wageningen, The Netherlands.

Rijtema, P.E. 1968. "Derived Meteorological Data: Transpiration", Proceedings of the Symposium on Agroclimatological Methods, Reading, 1966.

Rijtema, P.E. and Ryhiner, A.H., 1966. "De Lysimeters in Nederland", Verslagen Mededelingen en Hydrologische Communicaties TNO, 14:86-149.

Ritchie, J.T. 1972. "Model for Predicting Evaporation from a Row Crop with Incomplete Cover", Water Resources Research, 8:1204-1213.

Robinson, S.M. 1962. "Computing Wind Profile Parameters", Journal of the Atmospheric Sciences, 19:189-190.

Rosenberg, N.J., Blad, B.L. and Verma, S.B. 1983. "Microclimate, The Biological Environment", Wiley, New York.

Russell, G. 1980. "Crop Evaporation, Surface Resistance and Soil Water Status", Agricultural Meteorology, 21:213-226.

Seginer, I. 1973. "Aerodynamic Roughness of Vegetated Surfaces", Boundary-Layer Meteorology, 5:381-393.

Shaw, R.H. and Pereira, A.R. 1982. "Aerodynamic Roughness of a Plant Canopy: a Numerical Experiment", Agricultural Meteorology, 26:51-65.

Sherratt, D.J. and Wheater, H.S. 1984. "The Use of Surface Resistance - Soil Moisture Relationships in Soil Water Budget Models", Agricultural and Forest Meteorology, 31:143-157.

Shu Fen Sun 1982. "Moisture and Heat Transport in a Soil Layer Forced by Atmospheric Conditions", thesis presented to the University of Connecticut, Connecticut.

Shuttleworth, W.J. 1975. "The Concept of Intrinsic Surface Resistance: Energy Budgets at a Partially Wet Surface", Boundary-Layer Meteorology, 8:81-99.

Shuttleworth, W.J. 1976a. "Experimental Evidence for the Failure of the Penman-Monteith Equation in Partially Wet Conditions", Boundary-Layer Meteorology, 10:91-94.

Shuttleworth, W.J. 1976b. "A One-Dimensional Theoretical Description of the Vegetation-Atmosphere Interaction", Boundary-Layer Meteorology, 10:273-302.

Shuttleworth, W.J. 1978. "A simplified One-Dimensional Theoretical Description of the Vegetation-Atmosphere Interaction", Boundary-Layer Meteoroloy, 14:3-27.

Shuttleworth, W.J. 1979. "Below-Canopy Fluxes in a Simplified One-Dimensional Theoretical Description of the Vegetation-Atmosphere Interaction", Boundary-Layer Meteorology, 17:315-331.

Shuttleworth, W.J. and Wallace, J.S. 1985. "Evaporation from Sparse Crops - an Energy Combination Theory", Quarterly Journal of the Royal Meteorological Society, 111:839-853.

Sinclair, T.R., Murphy, C.E. and Knoerr, K.R. 1976. "Development and Evaluation of Simplified Models for Simulating Canopy Photosynthesis and Transpiration", Journal of Applied Ecology, 20:813-829.

Slabbers, P.J. 1977. "Surface Roughness of Crops and Potential Evapotranspiration", Journal of Hydrology, 34:181-191.

Slatyer, R.O and McIlroy, I.C. 1961. "Practical Microclimatology", CSIRO, Canberra.

Stanhill, G. 1969. "A Simple Instrument for the Field Measurement of Turbulent Diffusion Flux", Journal of Applied Meteorology, 8:509-513.

Stearns, C.R. 1970. "Determining Surface Roughness and Displacement Height", Boundary-Layer Meteorology, 1:102-111.

Szeicz, G., Endrodi, G. and Tajchman, S. 1969. "Aerodynamic and Surface Factors in Evaporation", Water Resources Research, 5:380-394.

Szeicz, G. and Long, I.F. 1969. "Surface Resistance of Crop Canopies", Water Resources Research, 5:622-633.

Tanner, C.B. 1963. "Energy Relations in Plant Communities", in "Environmental Control of Plant Growth", L.T. Evans, ed., Academic Press, New York.

Tanner, C.B. and Fuchs, M. 1968. "Evaporation from Unsaturated Surfaces: a Generalized Combination Method", Journal of Geophysical Research, 73:1299-1304.

Tanner, C.B. and Jury, W.A. 1976. "Estimating Evaporation and Transpiration from a Row Crop during Incomplete Cover", Agronomy Journal, 68:239-243.

Tanner, C.B. and Pelton, W.L. 1960. "Potential Evapotranspiration Estimates by the Approximate Energy Balance Method of Penman", Journal of Geophysical Research, 65:3391-3413.

Tetens, O., 1930. "Uber Einige Meteorologische Begriffe", Zeitung der Geophysik, 6:297-309.

Thom, A.S. 1971. "Momentum Absorption by Vegetation", Quarterly Journal of the Royal Meteorological Society, 97:414-428.

Thom, A.S. 1972. "Momentum, Mass and Heat Exchange of Vegetation", Quarterly Journal of the Royal Meteorological Society, 98:124-134.

Thom, A.S. 1975. "Momentum, Mass and Heat Exchange of Plant Communities", in "Vegetation and the Atmosphere", J.L. Monteith, ed., Vol. 1, Academic Press, London.

Thom, A.S. and Oliver, H.R. 1977. "On Penman's Equation for Estimating Regional Evaporation", Quarterly Journal of the Royal Meteorological Society, 103:345-357.

Thompson, N., Barrie I.A. and Ayles, M. 1981. "The Meteorological Office Rainfall and Evaporation Calculation System: MORECS", Hydrological Memorandum No 45, United Kingdom Meteorological Office.

Thornthwaite, C.W. 1948. "An Approach toward a Rational Classification of Climate", Geographical Review, 38:55-94.

Van Bavel, C.H.M. 1966. "Potential Evaporation: The Combination Concept and Its Experimental Verification", Water Resources Research, 2:455-467.

Van Bavel, C.H.M. 1967. "Changes in Canopy Resistance to Water Loss from Alfalfa Induced by Soil Water Depletion", Agricultural Meteorology, 4:165-176.

Van Zyl, W.H. and De Jager, J.M. 1987. "Accuracy of the Penman-Monteith Equation Adjusted for Atmospheric Stability", Agricultural and Forest Meteorology, 41:57-64.

Verma, S.B. and Barfield, B.J. 1979. "Aerial and Crop Resistances Affecting Energy Transport", in "Modification of the Aerial Environment of Crops", B. Barfield and J. Gerber, eds., ASAE, St. Joseph, Michigan.

Verma, S.B. and Rosenberg, N.J. 1977. "The Brown-Rosenberg Resistance Model of Evapotranspiration Modified Tests in an Irrigated Sorghum Field", Agronomy Journal, 69:332-335.

Waggoner, P.E. and Reifsnyder, W.E. 1968. "Simulation of the Temperature, Humidity and Evaporation Profiles in a Leaf Canopy", Journal of Applied Meteorology, 7:400-409.

Wallace, J.S., Roberts, J.M. and Sivakumar, M.V.K. 1990. "The Estimation of Transpiration from Sparse Dryland Millet using Stomatal Conductance and Vegetation Area Indices", Agricultural and Forest Meteorology, 51:35-49.

Wright, J.L. 1978. "Solar Radiation Data for Southern Idaho, 1965-1976", Technical Memorandum SRCRC 78-1, United States Department of Agriculture, Science and Education Administration.

Wright, J.L. 1982. "New Evapotranspiration Crop Coefficients", Journal of the Irrigation and Drainage Division, ASCE, 108:57-74.

Wright, J.L. 1988. "Daily and Seasonal Evapotranspiration and Yield of Irrigated Alfalfa in Southern Idaho", Agronomy Journal, 80:662-669.

Yaglom, A.M. 1977. "Comments on Wind and Temperature Flux-Profile Relationships", Boundary-Layer Meteorology, 11:89-102.

APPENDICES

Appendix A.
Hourly Surface Resistances

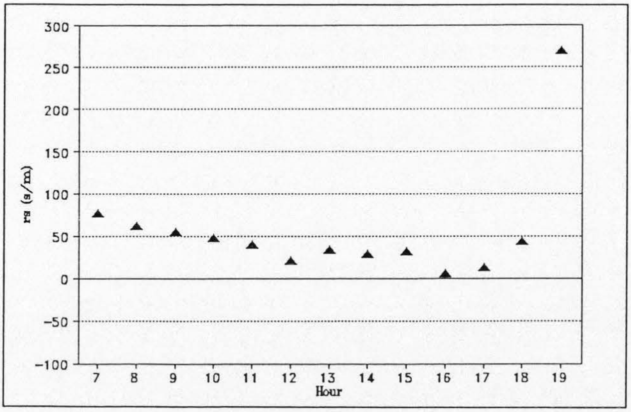

FIGURE A1. Computed Hourly Surface Resistance, July 11 1973 (Day of Year = 192).

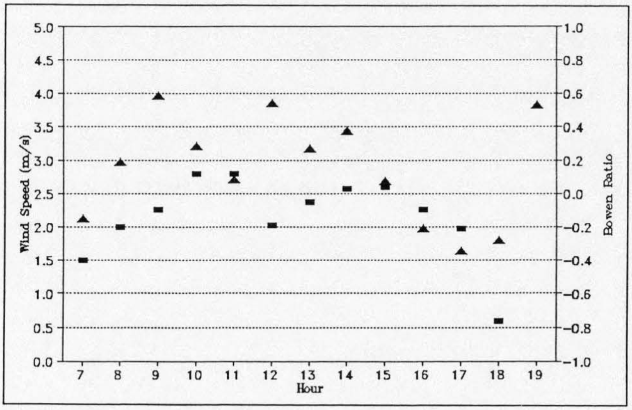

FIGURE A2. Hourly Wind Speed (△) and Bowen Ratio (□), July 11 1974 (Day of Year = 192).

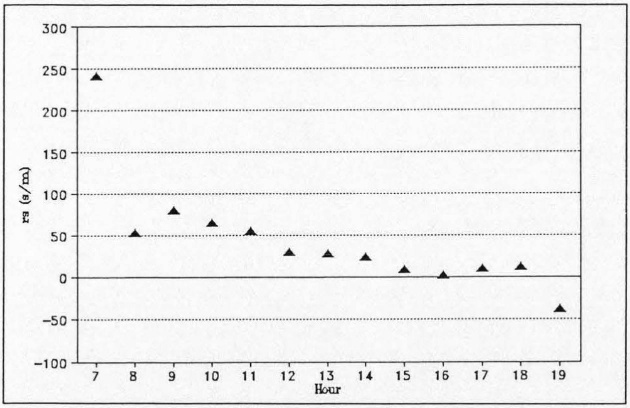

FIGURE A3. Computed Hourly Surface Resistance, July 11 1974 (Day of Year = 192).

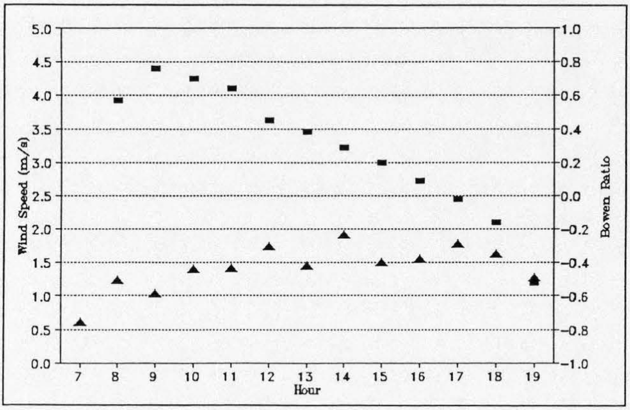

FIGURE A4. Hourly Wind Speed (△) and Bowen Ratio (□), July 11 1974 (Day of Year = 192).

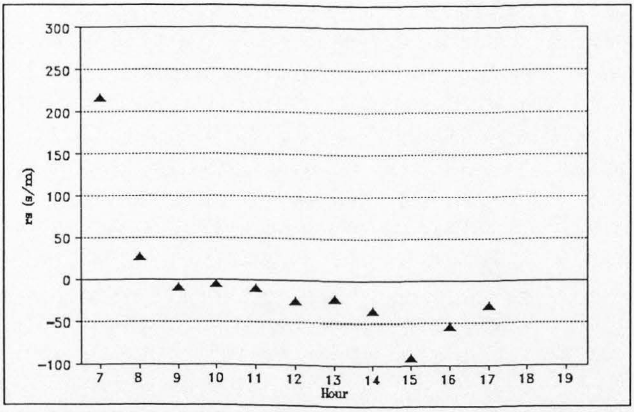

FIGURE A5. Computed Hourly Surface Resistance, July 21 1974 (Day of Year = 202).

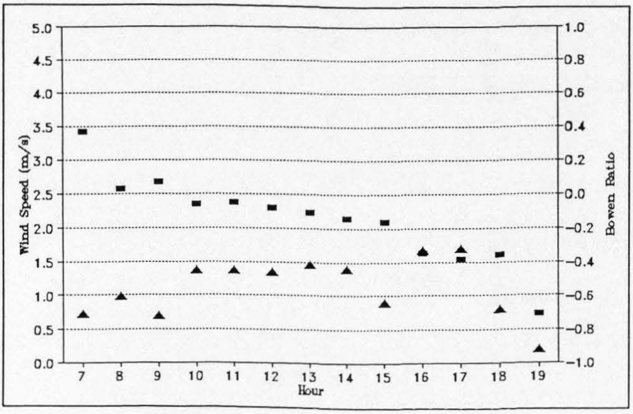

FIGURE A6. Hourly Wind Speed (△) and Bowen Ratio (□), July 21 1974 (Day of Year = 202).

Discussion

All days selected for Figs. A1 through A6 are for snap beans, prior to lodging. July 11 1973 (Figs. A1 and A2) has both negative and positive Bowen ratios, but thanks to high wind speeds throughout the day, all back-calculated hourly surface resistances have reasonable values.

July 11 1974 (Figs. A3 and A4), on the other hand, has low wind speeds throughout the day. The back-calculated hourly surface resistances follow the same trend as the Bowen ratio: as the Bowen ratio drops in the course of the day, surface resistance drops too.

July 21 1974 (Figs. A5 and A6) is a typical problem day. Wind speeds are low and Bowen ratios are negative throughout most of the day. As a result, the back-calculated hourly surface resistances are negative throughout most of the day too.

Appendix B.
Daily Surface Resistances

TABLE B1. Daily Surface Resistance (Snap Beans, 1973).

Scale: Weight:	Daily /	Hourly /	Hourly Rs	Hourly Rn	Hourly LE	
DOY	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	
142	649.2	1392.2	1459.9	1483.2	787.7	
143	1710.1	1689.0	2479.0	2543.8	777.8	
144	1917.9	2176.1	2930.3	3079.9	322.8	*
145	90.9	1774.3	1126.2	1155.2	47.7	*
146	671.3	1886.0	2581.1	2673.8	102.0	
147	853.3	1188.9	1851.6	1854.8	271.0	
148	932.9	2759.7	2723.0	2747.3	152.6	
149	5092.9	2608.2	2579.6	2503.1	768.4	
150	1055.2	2258.0	2503.3	2477.9	366.2	
153	685.5	1840.7	2088.2	2156.6	141.9	
154	741.9	1990.1	2291.2	2372.6	149.6	
156	1543.4	1894.7	2611.5	2755.9	1366.7	
157	1435.6	1708.5	2102.2	2107.6	1417.4	
158	1080.2	1774.0	1921.3	1941.0	373.9	
159	1677.7	1599.2	1923.7	2003.0	937.6	
160	872.8	2212.2	2771.1	2821.1	299.6	
161	1129.5	2457.1	2425.6	2386.1	287.0	
162	1280.8	2312.6	1422.1	1432.3	875.0	
163	805.6	1744.2	1550.9	1416.2	561.7	
164	78.8	1185.5	169.7	147.3	75.8	*
165	42.2	1645.7	1967.5	2002.4	47.1	*
166	22.7	141.9	73.4	68.8	32.2	
167	88.6	699.5	265.2	207.7	73.4	
168	18.6	1151.2	1069.5	861.7	21.8	*
169	124.4	1597.0	2328.2	2279.2	35.1	
170	415.7	1124.9	1016.6	904.6	302.2	
171	393.6	1181.1	626.1	633.8	427.5	
173	334.9	1607.5	911.4	804.4	159.4	
174	406.3	1689.3	454.1	455.5	250.5	
175	298.7	1466.8	326.2	288.7	253.0	
178	43.4	394.8	40.8	34.8	39.3	
179	128.6	554.7	104.8	57.0	73.0	
180	61.9	337.6	44.9	32.5	33.5	*
181	95.6	389.9	63.6	59.7	73.2	
182	195.4	1017.4	153.9	154.9	132.8	
183	123.8	469.0	94.0	94.7	80.2	
184	118.5	221.1	116.7	119.8	116.3	
185	54.5	260.7	65.6	59.0	48.4	*
186	28.0	25.6	27.9	28.4	26.4	
187	41.9	68.8	32.9	31.3	36.5	
188	37.6	72.6	26.5	24.5	27.3	
189	21.7	60.7	27.2	25.1	24.0	
190	25.7	128.5	20.6	18.6	19.6	
191	99.7	117.7	58.8	58.2	65.6	*
192	68.9	134.1	34.4	32.2	58.2	
195	28.8	294.3	21.8	19.8	30.5	*
196	-6.5	302.1	28.6	7.9	10.3	

TABLE B1 (Continued)

197	-3.4	216.1	16.7	8.4	13.1	
198	26.1	90.0	18.6	16.7	29.3	*
199	25.0	91.4	8.3	6.2	21.0	
200	95.3	123.9	103.3	100.2	100.0	*
205	5.5	532.4	33.0	19.1	14.3	
206	-31.5	126.4	13.2	8.1	8.2	*
208	-11.8	181.0	24.5	11.4	10.9	
210	22.7	297.7	7.0	5.5	23.8	
211	44.2	608.4	24.2	19.2	27.4	
212	0.9	321.6	29.8	11.9	14.6	
213	-34.0	685.6	36.7	18.6	18.1	
214	35.3	181.1	38.8	23.0	29.1	
215	46.0	94.1	34.3	24.5	33.6	*
216	4.0	336.6	18.2	14.5	16.4	
217	-0.9	916.4	93.1	43.1	27.2	
218	57.0	164.9	50.3	50.3	50.3	*
219	46.7	324.5	43.1	40.4	40.6	
220	26.3	455.2	101.6	66.8	45.2	
221	87.2	132.3	93.5	83.9	91.9	
222	55.1	569.6	59.7	44.3	52.0	
223	66.6	434.8	142.0	54.0	53.4	
224	84.9	154.7	58.9	53.2	70.7	
225	66.7	350.7	64.1	50.9	54.0	*
226	52.1	381.4	123.6	51.8	52.6	
227	125.4	439.9	159.2	109.7	84.4	
228	92.0	375.1	121.8	94.1	80.6	
229	107.8	181.8	75.9	71.8	74.5	
230	110.7	521.1	115.8	78.8	77.2	
231	127.0	378.2	112.4	107.4	113.8	
232	145.4	640.4	153.4	123.5	126.7	
233	190.6	502.9	202.7	185.4	193.9	*
234	160.7	645.1	135.6	127.5	136.9	*
235	157.5	425.6	150.8	131.4	158.4	
236	176.5	299.8	143.6	145.1	155.8	
237	209.3	601.9	168.1	164.7	178.7	
238	281.7	685.1	248.3	243.9	233.8	
239	515.5	1535.0	934.0	807.2	444.7	
Avg	24.8	292.3	37.3	27.2	30.8	
Std	34.1	212.4	27.0	22.8	21.1	

Remarks:

* = precipitation or irrigation
Avg = average for period with constant rs
Std = standard deviation for period with constant rs
Period with constant rs = day of year 190-220
All hourly values filtered prior to averaging (0-5000)

TABLE B2. Daily Surface Resistance (Snap Beans, 1974).

Scale: / Weight:	Daily /	Hourly /	Hourly Rs	Hourly Rn	Hourly LE	
DOY	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	
143	1022.8	2009.1	1258.5	1263.3	914.1	
146	3409.6	2483.0	3541.3	3711.7	1657.6	
147	1600.2	2070.6	2532.7	2568.5	453.3	
148	2581.2	2167.5	2967.7	3053.6	836.4	
151	1707.2	2610.8	2776.0	2713.4	577.7	
152	3114.8	2742.8	2505.2	2498.3	755.6	
153	2587.7	2882.4	2628.0	2564.5	1342.2	
154	2087.1	2896.2	2921.5	2907.4	319.3	
155	1158.1	2322.8	2641.3	2691.2	297.9	*
156	176.7	1853.8	1143.9	987.9	99.1	*
157	665.8	2427.9	1789.8	1725.9	262.7	
158	901.7	1587.0	1600.5	1604.3	47.6	
159	1167.6	2285.4	2676.7	2718.6	514.9	
160	1896.2	2266.1	1890.4	1872.5	992.2	
161	1833.6	2105.8	2240.1	2278.9	1246.6	
163	1628.3	2172.0	2017.3	2008.0	1564.8	
164	1929.4	2552.5	1891.8	1904.5	1542.4	
165	289.4	1265.8	542.2	436.4	193.8	*
166	266.6	619.4	339.6	305.1	299.9	
169	450.2	1328.5	407.2	399.9	405.7	
170	402.4	1491.5	438.6	376.1	309.8	
171	465.6	2066.3	1177.8	1062.9	315.6	
172	185.9	685.4	278.6	273.2	178.8	*
174	228.3	516.1	176.1	171.4	186.9	
175	253.5	631.7	187.3	190.1	204.7	
176	214.0	585.2	199.2	200.2	193.6	
177	297.2	845.8	251.5	260.4	249.7	
178	236.0	601.2	189.3	194.1	198.7	
179	246.8	873.0	226.9	201.3	205.8	
180	271.9	763.7	226.5	205.3	223.2	
181	242.1	521.6	191.5	193.4	202.9	
182	86.0	354.3	90.9	93.4	70.3	*
183	49.2	82.7	44.7	42.2	49.9	
184	36.5	406.9	70.9	57.5	52.2	
185	70.7	270.3	77.0	76.5	69.8	
186	75.8	102.5	57.8	57.3	63.0	
187	104.5	218.9	59.1	54.1	73.6	
188	79.2	301.0	58.6	45.7	56.1	
190	34.7	271.2	41.9	38.3	42.5	
191	88.5	276.3	180.9	192.0	105.0	*
192	32.0	601.6	50.8	34.2	33.4	
193	28.1	395.2	27.5	24.2	22.2	
194	30.2	262.0	28.2	26.7	25.4	
195	47.3	61.5	22.5	19.6	22.9	
197	12.9	330.2	19.8	7.4	19.7	
198	22.0	152.9	20.5	11.3	27.3	
199	-9.2	473.2	17.9	4.6	11.8	

TABLE B2 (Continued)

200	33.2	186.4	18.7	13.3	28.4	*
201	12.8	242.4	6.5	6.1	9.7	
202	-21.3	443.4	7.4	3.3	7.8	
203	3.0	169.4	9.3	5.5	13.0	
204	26.9	91.5	16.2	12.7	22.3	
205	43.7	92.7	32.9	29.1	38.8	
207	18.1	158.7	27.8	22.2	23.4	
208	30.9	134.6	15.5	9.1	19.8	*
209	-1.0	157.9	7.3	4.6	10.5	
210	21.3	77.1	14.0	10.6	19.3	
211	23.6	210.4	21.9	12.5	25.6	
212	6.4	133.0	10.9	5.6	16.1	
213	93.8	162.7	53.5	45.7	63.0	
214	20.4	383.9	72.3	18.0	24.2	
215	31.9	192.1	22.9	18.1	22.3	
216	19.9	376.8	26.5	22.6	26.3	
217	30.8	326.4	34.5	18.6	28.6	
218	64.5	552.4	52.7	40.7	55.5	*
219	45.4	213.0	67.7	52.4	49.9	*
220	66.3	776.1	53.6	52.0	56.8	
221	49.9	355.0	57.6	56.6	50.8	*
222	44.4	457.0	51.1	46.2	45.0	
223	45.4	278.7	42.7	41.7	41.0	
224	51.8	132.1	41.6	39.7	38.5	
225	76.8	115.8	56.2	49.8	64.3	
226	83.3	75.0	68.2	68.5	69.4	
227	79.6	285.0	92.6	93.5	76.8	
228	139.0	121.5	84.6	84.5	74.2	
229	101.4	419.3	106.7	101.8	91.0	
230	118.4	297.4	125.4	122.7	107.2	
231	123.2	155.9	111.2	109.4	121.1	
232	189.6	211.5	146.3	145.0	145.1	
233	188.7	519.3	207.9	200.2	176.6	
234	269.8	420.2	201.2	206.9	198.2	
235	230.1	464.9	238.9	223.5	197.0	
236	232.8	464.1	237.5	227.1	203.1	
237	280.1	768.4	262.1	239.4	232.2	
238	330.6	665.9	310.3	304.8	272.2	
239	443.9	726.3	367.5	372.8	352.0	
240	466.7	1112.1	466.6	479.7	449.4	
Avg	29.6	272.6	33.9	26.2	30.1	
Std	25.1	168.8	32.9	34.4	19.9	

Remarks:

* = precipitation or irrigation
Avg = average for period with constant rs
Std = standard deviation for period with constant rs
Period with constant rs = day of year 190-220
All hourly values filtered prior to averaging (0-5000)

TABLE B3. Daily Surface Resistance (Winter Wheat, 1978).

Scale:	Daily	Hourly	Hourly	Hourly	Hourly	
Weight:	/	/	Rs	Rn	LE	
DOY	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	
74	23.3	129.9	253.4	241.7	54.4	*
75	108.1	374.5	462.2	404.4	138.5	
76	122.8	202.4	94.1	88.9	65.9	
77	14.8	94.9	79.6	69.4	30.5	
78	9.6	372.7	183.0	170.2	58.9	
80	83.7	779.2	198.5	94.2	59.4	
81	143.0	376.6	308.5	311.5	101.1	*
82	140.0	695.0	1164.7	1207.1	154.2	*
83	25.5	126.1	26.2	27.8	24.9	*
84	12.8	252.6	201.8	206.3	81.6	
85	71.3	252.5	121.7	120.6	51.4	
86	35.9	285.7	142.9	90.9	35.2	
87	8.1	229.4	76.5	80.6	57.3	
88	66.7	212.1	51.6	54.1	43.4	
89	34.7	273.6	42.6	44.6	47.9	
90	148.1	719.3	586.1	628.8	124.5	
91	98.4	789.3	365.3	382.0	80.9	*
92	1.3	13.8	25.6	26.7	19.6	
93	72.8	341.8	640.8	711.1	76.7	*
94	171.5	662.7	654.2	614.1	90.0	*
95	45.2	108.4	104.5	97.8	56.6	
97	194.7	804.1	1155.3	1190.0	184.3	*
98	71.7	346.2	381.0	415.0	45.4	*
99	41.4	52.0	51.7	52.2	41.7	
100	63.9	221.7	67.0	58.5	50.6	
101	26.0	364.6	32.0	29.9	33.9	
102	72.2	668.0	64.9	62.4	65.4	
104	55.2	350.8	54.3	50.4	50.7	*
105	84.4	351.7	127.8	105.7	70.9	*
106	85.0	1031.0	1285.5	1405.9	40.3	*
107	31.7	27.4	32.3	31.2	27.8	
108	55.8	216.6	66.0	63.6	60.7	
109	71.3	292.4	50.6	47.6	52.1	
110	92.4	490.7	241.8	226.1	75.0	*
111	26.7	98.4	24.6	22.9	21.3	
112	35.9	205.4	41.6	43.0	36.8	
113	23.4	187.5	42.7	34.6	30.6	
114	53.4	261.7	33.0	33.7	37.6	
115	64.5	708.4	294.3	247.8	65.5	*
116	49.8	118.6	91.0	95.8	51.7	*
117	168.9	961.1	1758.9	1817.4	150.0	*
118	31.8	222.0	25.9	25.5	24.7	
119	40.1	209.3	25.4	25.7	26.5	
121	23.6	76.1	22.1	21.5	20.8	*
122	25.2	102.3	45.8	23.2	27.2	
124	30.7	51.3	27.7	26.2	34.4	
125	65.6	466.8	557.4	590.4	46.0	*

TABLE B3 (Continued)

126	56.5	320.0	256.5	230.8	56.9	*
127	27.4	66.1	23.6	24.1	23.9	
128	19.4	426.0	19.6	18.8	21.4	
129	30.8	371.8	37.7	33.4	35.4	*
130	28.8	160.4	30.3	29.7	29.9	*
131	14.2	766.7	1095.1	1270.7	39.6	*
133	51.1	789.3	64.7	49.5	48.7	
136	29.6	304.7	26.7	20.1	22.3	*
138	37.3	27.9	28.2	27.9	25.0	
139	31.5	229.8	25.9	23.8	24.0	*
140	31.9	467.0	32.9	26.0	27.5	
141	24.5	141.5	37.5	34.8	32.7	
142	28.2	87.0	23.5	23.0	26.7	
143	40.9	245.9	26.8	24.9	28.6	
144	71.3	1036.2	717.1	643.7	56.2	*
145	31.0	90.0	23.2	23.5	22.6	*
146	19.0	89.5	37.2	35.6	29.1	
147	19.4	95.0	24.4	24.3	24.3	
148	31.3	131.7	29.0	28.3	28.0	
149	26.8	49.6	30.5	30.4	28.7	
150	30.8	37.2	25.5	24.9	27.8	
151	17.9	58.7	23.5	22.9	23.5	
154	53.9	850.8	515.3	454.1	33.8	*
155	38.1	546.8	181.8	172.6	43.8	
156	26.4	76.2	29.8	25.4	27.7	
157	32.1	242.2	28.3	27.1	37.7	
161	35.6	263.7	46.0	44.0	46.9	
162	30.3	289.8	28.0	27.3	33.2	
163	60.8	254.0	42.4	38.7	43.4	
164	35.4	632.3	48.4	26.9	34.1	
166	35.3	48.2	30.6	28.8	33.3	
167	40.6	107.3	32.6	31.0	35.4	
168	32.6	401.3	27.8	23.8	32.2	
169	52.7	315.3	51.7	51.4	42.3	*
170	40.5	217.1	33.5	32.6	35.3	
171	40.3	333.4	53.7	41.9	36.5	*
172	28.3	375.5	42.7	28.9	31.4	
173	34.2	570.2	52.5	33.7	38.6	
174	48.8	487.9	33.0	30.4	37.2	
175	63.6	110.6	47.5	46.9	48.3	*
176	43.5	89.3	38.1	36.4	39.7	
177	49.8	498.9	46.7	39.9	46.2	
178	36.6	231.5	43.6	35.6	38.1	
179	36.6	397.9	43.0	37.4	38.7	
180	43.6	475.1	143.4	75.7	40.6	
181	43.2	236.1	36.8	36.2	36.3	
183	45.3	554.1	148.7	89.6	40.6	
184	37.9	672.1	162.8	68.0	45.9	*
185	40.1	25.4	38.2	38.3	33.3	*
186	33.4	182.9	42.9	40.8	39.6	
187	27.5	159.2	31.5	31.3	30.0	
188	70.3	122.1	35.2	34.9	34.5	

TABLE B3 (Continued)

189	34.3	145.5	36.7	36.9	35.6	
190	34.3	140.9	51.1	35.4	38.2	
191	47.2	646.8	43.1	42.4	44.0	
192	51.4	206.5	38.7	38.6	37.6	
193	31.2	165.8	36.6	21.4	22.2	*
194	20.8	52.0	43.3	31.0	27.2	
195	58.1	352.2	52.8	49.7	51.4	
196	50.1	310.3	43.6	42.9	46.6	
197	38.5	68.6	40.0	39.4	37.3	
198	59.5	159.2	57.3	52.0	51.1	
199	46.8	140.2	52.6	50.8	50.6	
200	67.0	504.0	58.2	55.0	55.3	
201	61.4	230.6	48.3	50.3	46.2	
204	92.9	321.3	75.6	67.4	65.5	
205	71.1	269.3	61.4	57.6	57.4	
206	64.1	287.1	57.1	55.9	56.5	
207	70.3	352.5	62.2	60.4	59.9	
209	76.9	339.4	79.8	64.4	56.5	*
210	104.8	67.8	81.7	84.3	78.7	
211	137.9	60.7	105.2	109.0	100.0	
212	154.4	114.6	151.3	153.5	140.0	
213	167.5	110.4	146.6	148.5	136.6	*
214	195.8	118.2	191.5	193.1	170.9	
215	244.2	301.2	230.8	238.7	214.9	
216	298.5	582.0	307.1	301.4	268.4	
217	337.6	503.0	340.6	346.9	284.1	
218	444.2	880.8	428.9	431.4	381.1	
219	574.3	665.9	572.2	575.5	487.1	
220	764.8	696.1	927.4	848.1	661.2	
221	1195.4	1645.6	1473.5	1435.5	1005.7	
222	1715.2	1515.2	1917.6	1938.3	1328.5	
223	1379.9	1347.6	1941.6	1882.3	957.2	
224	1239.6	2002.6	3660.5	3644.1	1051.8	
225	605.8	1588.0	1429.2	1360.2	576.8	
226	1030.4	1053.0	1145.5	1152.6	800.6	
Avg	39.1	294.1	90.6	84.4	36.3	
Std	13.3	226.3	175.9	187.7	9.0	

Remarks:

* = precipitation or irrigation
Avg = average for period with constant rs
Std = standard deviation for period with constant rs
Period with constant rs = day of year 125-200
All hourly values filtered prior to averaging (0-5000)

TABLE B4. Daily Surface Resistance (Spring Wheat, 1979).

Scale: / Weight:	Daily /	Hourly /	Hourly Rs	Hourly Rn	Hourly LE	
DOY	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	
101	816.8	901.0	1925.1	2026.7	393.5	
102	724.1	1151.6	1827.8	1751.3	483.4	*
103	663.9	1157.0	2383.9	2361.0	505.6	*
104	13452.5	2581.2	3702.4	3680.7	1874.2	
105	1862.8	2363.8	3493.1	3469.7	1001.7	
106	4157.8	3068.8	4398.8	4492.0	1365.9	*
107	545.4	1864.0	2595.3	2535.9	335.2	*
108	587.0	969.6	1692.3	1719.5	323.2	
109	797.2	1346.3	2455.3	2388.7	464.1	
110	4243.9	1787.5	3757.4	3864.7	1816.8	
111	25752.5	2775.2	4431.4	4485.4	1880.5	
112	10296.3	2572.4	4366.2	4435.5	2314.4	
113	331.7	932.3	1640.3	1569.4	358.2	*
114	103.7	699.9	864.9	874.1	153.9	*
115	591.2	583.7	1195.8	1155.4	518.8	
116	3243.1	1733.6	3496.0	3524.4	1354.4	
117	3873.9	1760.8	2668.4	2647.2	821.9	
118	279.7	829.1	714.1	684.6	410.1	*
119	2306.7	1516.8	3119.9	3146.7	1206.6	
120	7325.9	2337.6	3673.7	3659.6	2146.1	
121	416.2	2449.3	3279.1	3437.3	98.4	*
122	2.7	426.6	173.4	151.5	32.6	*
123	7.7	152.8	69.6	48.1	33.4	
124	256.2	1219.1	1218.4	1252.4	177.3	
125	607.7	2276.9	1765.9	1727.2	351.6	*
126	14.5	212.0	61.7	54.5	33.6	*
127	92.9	1579.4	1366.3	1338.4	107.0	*
128	29.4	231.3	24.3	24.2	22.4	*
129	-40.0	108.6	91.4	98.7	40.9	*
130	126.1	420.1	230.9	225.6	126.7	
131	324.4	1291.6	699.4	653.3	252.0	
132	661.1	1279.4	2093.1	2053.2	633.4	
133	817.4	987.6	1506.3	1466.0	484.7	
134	1054.0	1427.4	1262.4	1199.2	836.3	
139	452.8	1135.4	424.9	431.4	393.5	
140	391.4	681.4	462.0	466.5	407.2	
141	305.8	680.5	292.3	291.7	280.9	
142	292.3	696.6	430.2	425.3	360.2	
143	222.2	883.6	227.3	201.6	180.5	*
144	72.3	277.8	104.4	87.2	72.7	*
145	114.8	148.9	128.7	135.0	113.3	
146	111.8	683.8	233.0	177.0	126.8	
147	98.3	589.8	92.6	90.3	94.5	
148	110.6	648.7	110.1	88.0	107.8	
149	111.8	280.7	103.7	99.0	98.7	
150	83.7	350.1	115.1	100.1	94.6	
151	61.0	278.8	81.8	84.3	76.2	

TABLE B4 (Continued)

152	33.3	181.4	68.3	65.7	61.7	
153	42.4	420.9	60.7	61.7	60.2	
154	45.8	523.9	56.5	55.9	57.2	
156	69.6	304.8	59.3	57.8	58.4	
157	65.2	323.0	57.2	53.6	67.8	
158	58.8	145.3	60.1	45.9	54.1	
159	23.5	71.2	39.8	39.3	38.7	*
160	16.3	281.3	68.1	41.9	40.8	
161	20.9	152.3	22.7	23.2	29.3	
162	33.8	104.6	57.0	52.3	53.1	
163	23.8	313.3	83.3	37.0	37.5	
164	45.0	138.6	34.0	32.8	39.6	
165	26.3	248.6	25.7	24.8	25.9	
166	32.0	431.2	39.9	33.8	36.6	
167	28.1	781.9	11.9	8.0	17.0	
168	62.0	1188.1	693.7	693.1	60.1	*
169	55.9	616.9	212.5	196.5	46.5	*
170	38.3	74.5	27.3	27.0	26.7	
171	21.7	30.0	22.7	20.7	21.6	*
172	22.3	78.3	30.1	29.0	23.2	*
173	14.9	203.5	25.7	14.9	19.5	
174	37.8	514.3	73.2	25.3	28.7	*
175	9.1	308.9	8.3	8.1	13.1	
176	10.4	181.3	11.4	10.7	13.6	
177	7.4	188.7	25.4	22.4	26.0	
178	51.3	272.4	36.2	33.4	38.3	
179	0.4	462.6	3.7	2.7	14.0	
180	32.1	985.4	68.7	23.1	31.6	
181	34.9	314.7	33.1	30.6	39.9	
182	32.5	336.3	23.7	20.6	29.2	
183	48.7	53.9	30.4	27.7	34.1	
184	43.2	160.4	33.5	32.2	36.0	
185	37.4	88.5	30.9	27.5	30.7	
186	41.8	502.4	42.5	30.5	39.4	
187	17.3	447.7	17.0	15.0	19.5	
188	38.1	81.1	29.8	28.3	29.8	*
189	29.3	235.4	25.2	24.7	24.5	
190	28.2	264.6	35.4	23.2	23.1	
191	34.9	223.2	56.1	40.1	47.0	
192	28.0	109.7	28.6	28.3	28.3	
193	30.8	243.6	34.3	31.5	33.0	
194	40.3	77.8	31.5	30.1	30.4	
195	24.7	194.6	30.9	29.2	29.4	
196	4.6	366.5	26.0	21.5	23.8	
197	11.0	328.8	58.2	11.4	13.0	
198	30.7	200.8	12.8	12.9	13.2	
199	25.7	607.6	19.7	17.5	17.6	
200	27.1	245.3	59.7	29.2	15.9	
201	21.6	391.2	25.4	16.4	17.1	
202	14.2	157.8	24.9	25.3	27.8	*
203	34.3	498.5	160.1	139.3	117.4	
204	29.7	120.0	27.9	28.8	27.2	

TABLE B4 (Continued)

205	28.8	63.0	33.5	31.4	30.7	
206	30.1	338.1	88.9	43.5	33.7	
207	38.4	271.1	42.3	39.9	39.7	
208	33.7	485.6	42.3	36.6	33.5	*
209	40.1	70.9	40.0	39.8	39.6	
210	50.6	80.1	50.8	49.0	47.5	
211	68.0	559.1	68.1	63.2	61.8	
212	101.1	901.3	88.3	82.5	82.0	
213	121.2	434.4	96.5	99.1	94.6	
214	154.0	187.1	130.6	130.6	127.4	
217	242.2	553.5	241.9	237.0	200.0	
220	290.3	486.3	344.8	338.2	216.0	
221	451.7	822.7	511.9	525.2	418.0	
222	658.5	895.0	867.8	893.8	647.1	
223	1089.5	2029.2	1302.2	1173.8	758.3	
224	788.5	1709.9	1653.7	1570.6	564.3	*
225	165.5	690.8	415.9	410.0	117.9	*
226	248.9	1119.2	1096.1	1112.9	204.2	*
227	398.7	1177.9	1187.6	1222.4	456.0	
228	1009.1	1058.1	1773.9	1794.1	935.3	
229	1054.4	1730.9	2179.1	2155.0	455.3	
230	1814.0	1274.4	2419.0	2509.1	688.9	
231	1293.5	1402.3	2525.2	2576.1	710.1	
Avg	29.8	296.4	54.4	45.5	31.7	
Std	12.9	231.5	96.9	96.3	16.1	

Remarks:

* = precipitation or irrigation
Avg = average for period with constant rs
Std = standard deviation for period with constant rs
Period with constant rs = day of year 160-210
All hourly values filtered prior to averaging (0-5000)

TABLE B5. Surface Resistance (Bare Soil, 1977).

Scale:	Daily	Hourly	Hourly	Hourly	Hourly
Weight:	/	/	Rs	Rn	LE
DOY	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)	rs (s/m)
222	38.3	114.0	181.2	177.8	120.3
223	56.3	69.3	95.6	94.2	72.5
224	42.5	261.9	205.7	200.7	131.1
225	101.3	157.6	245.3	236.3	170.9
226	322.9	283.2	529.1	524.6	379.8
227	872.0	908.8	1736.2	1776.0	1459.3
228	1332.7	1469.8	2355.0	2421.5	1919.2
229	1136.3	905.8	1762.2	1817.6	1062.9
245	150.2	139.9	222.1	204.0	156.8
246	24.0	312.6	207.5	216.4	91.2
247	28.5	179.5	114.3	113.9	72.4
248	100.5	419.0	122.4	125.6	108.6
249	324.8	263.3	468.6	474.9	354.7
250	895.0	1020.5	1575.8	1657.5	1142.1
251	374.5	808.3	828.7	860.0	377.7
252	1797.2	2171.3	2793.6	3038.4	1915.8

Remark:

All hourly values filtered prior to averaging (0-5000)

Appendix C.
Environmental Influences on Daily Surface Resistances

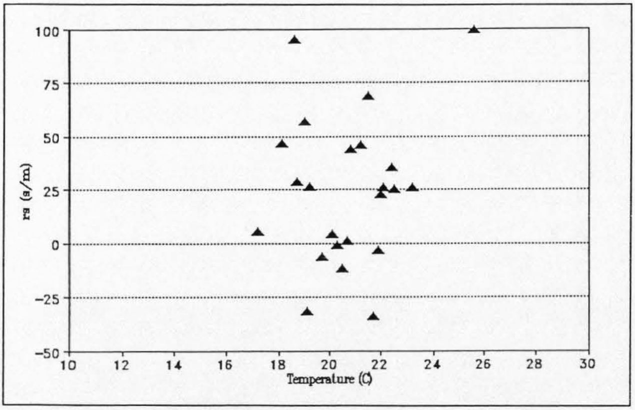

FIGURE C1. Computed Daily Surface Resistance versus Temperature (Snap Beans, 1973).

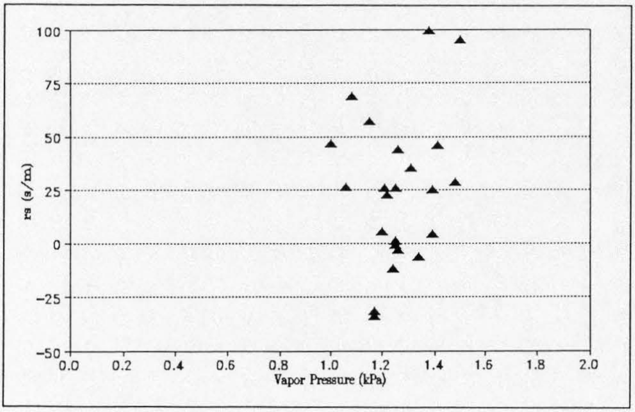

FIGURE C2. Computed Daily Surface Resistance versus Vapor Pressure (Snap Beans, 1973).

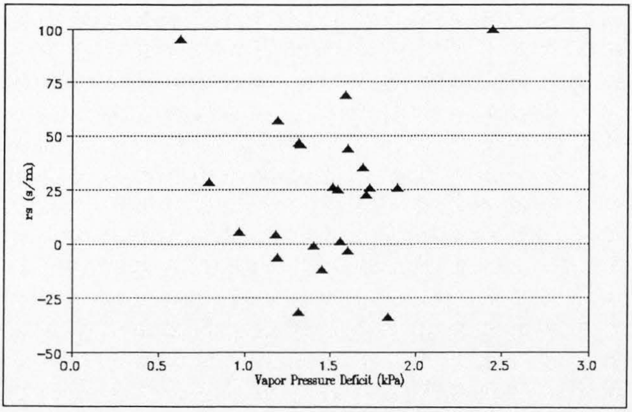

FIGURE C3. Computed Daily Surface Resistance versus Vapor Pressure Deficit (Snap Beans, 1973).

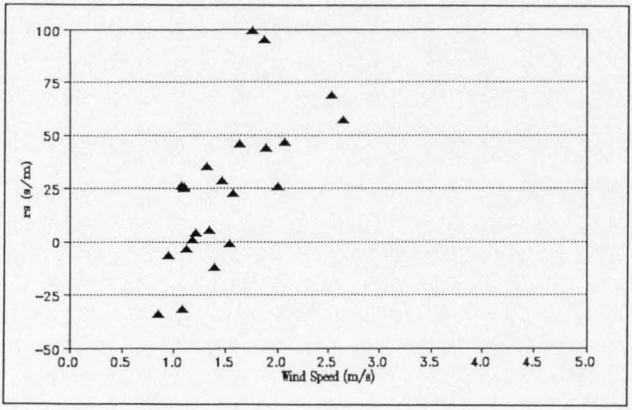

FIGURE C4. Computed Daily Surface Resistance Versus Wind Speed (Snap Beans, 1973).

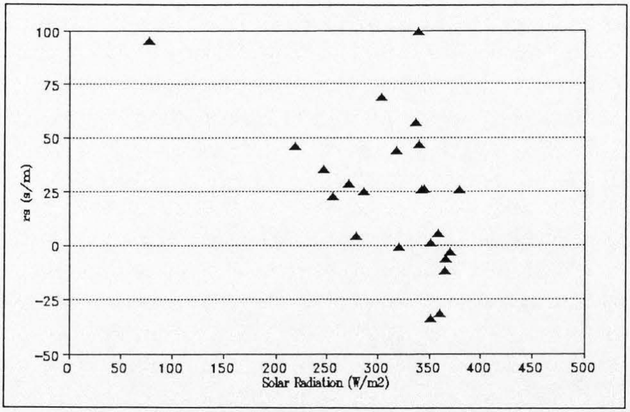

FIGURE C5. Computed Daily Surface Resistance versus Solar Radiation (Snap Beans, 1973).

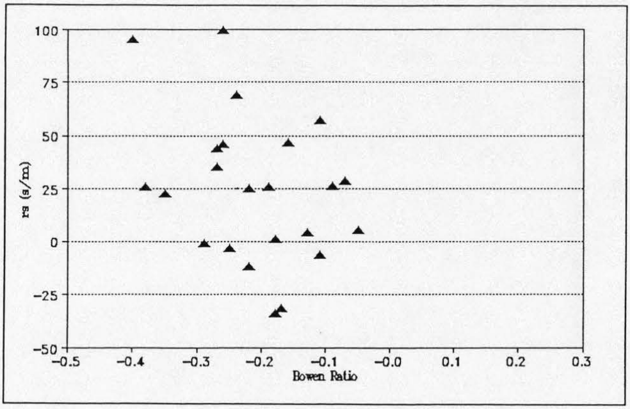

FIGURE C6. Computed Daily Surface Resistance versus Bowen Ratio (Snap Beans, 1973).

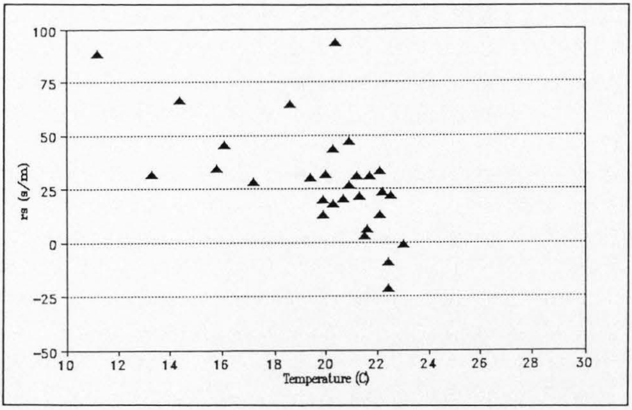

FIGURE C7. Computed Daily Surface Resistance versus Temperature (Snap Beans, 1974).

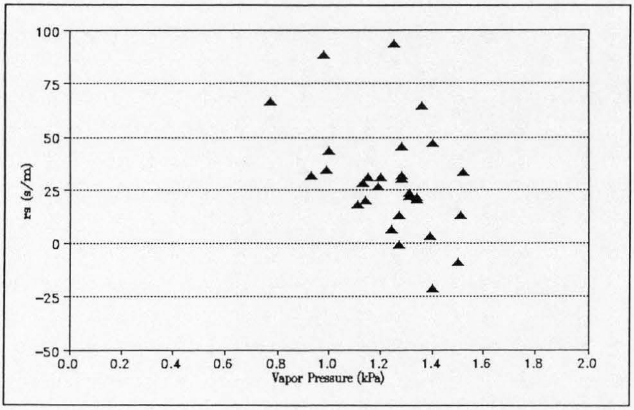

FIGURE C8. Computed Daily Surface Resistance versus Vapor Pressure (Snap Beans, 1974).

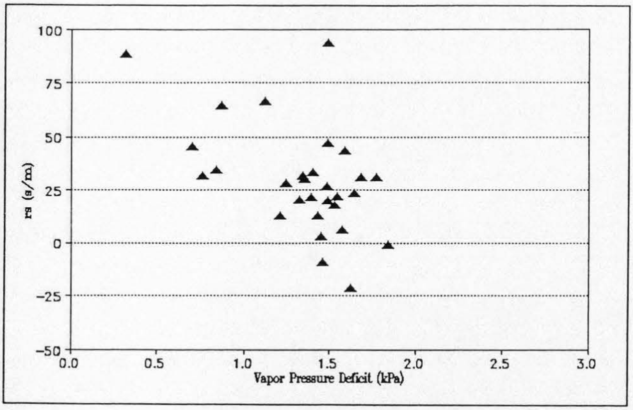

FIGURE C9. Computed Daily Surface Resistance versus Vapor Pressure Deficit (Snap Beans, 1974).

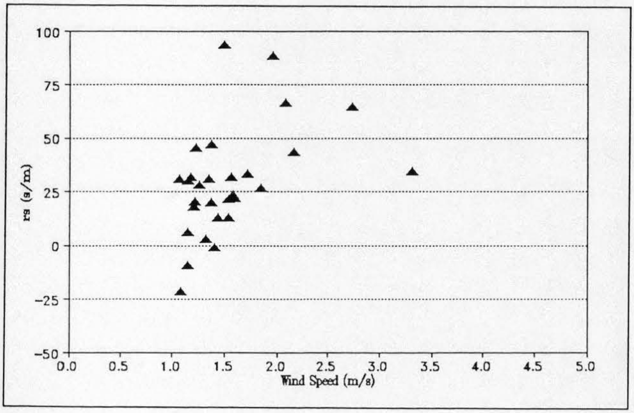

FIGURE C10. Computed Daily Surface Resistance Versus Wind Speed (Snap Beans, 1974).

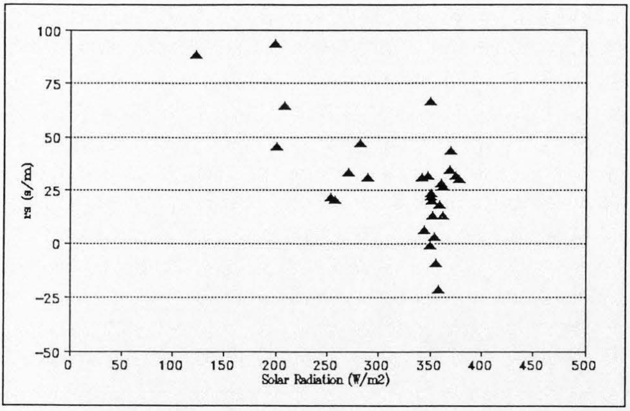

FIGURE C11. Computed Daily Surface Resistance versus Solar Radiation (Snap Beans, 1974).

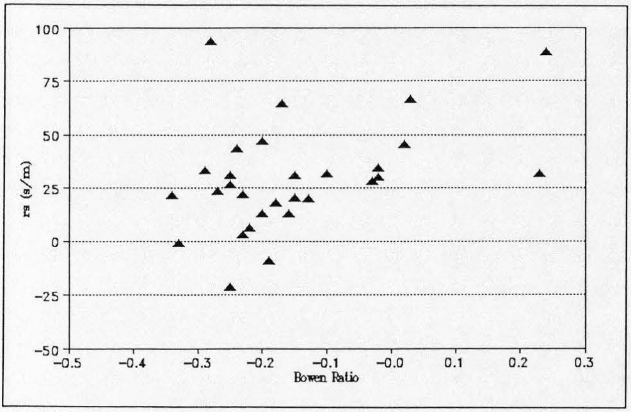

FIGURE C12. Computed Daily Surface Resistance versus Bowen Ratio (Snap Beans, 1974).

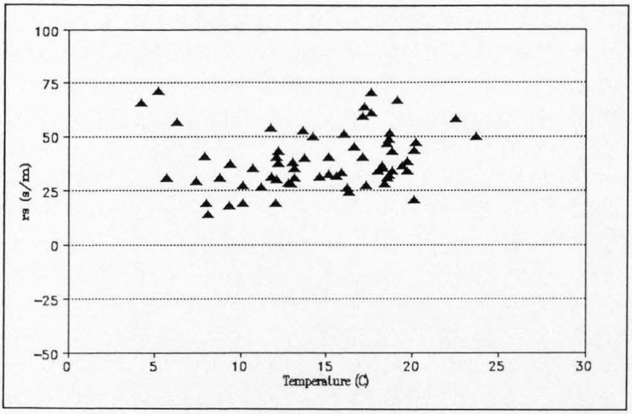

FIGURE C13. Computed Daily Surface Resistance versus Temperature (Winter Wheat, 1978).

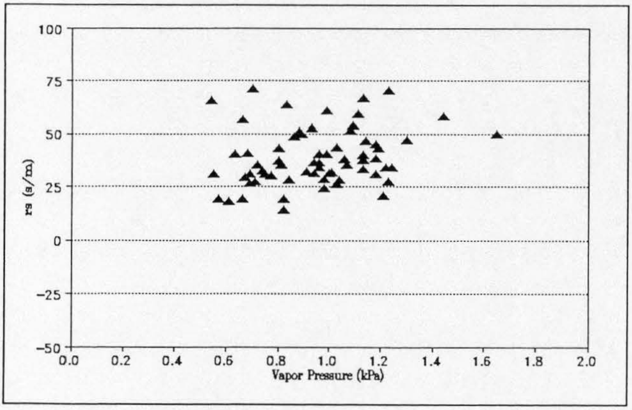

FIGURE C14. Computed Daily Surface Resistance versus Vapor Pressure (Winter Wheat, 1978).

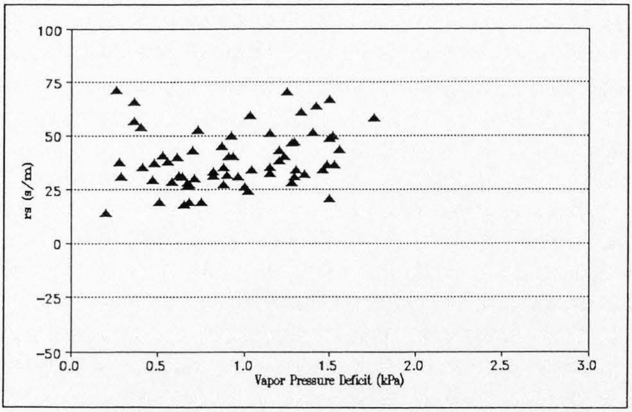

FIGURE C15. Computed Daily Surface Resistance versus Vapor Pressure Deficit (Winter Wheat, 1978).

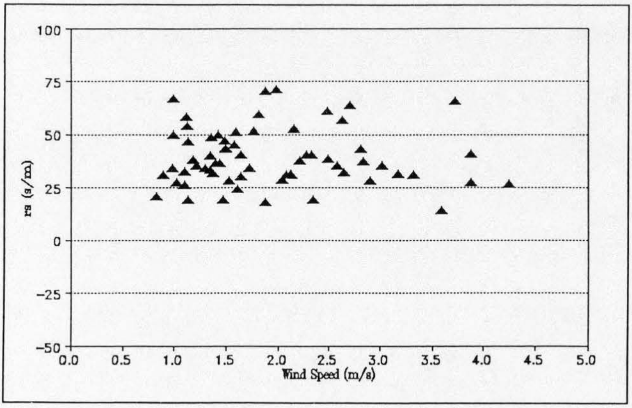

FIGURE C16. Computed Daily Surface Resistance Versus Wind Speed (Winter Wheat, 1978).

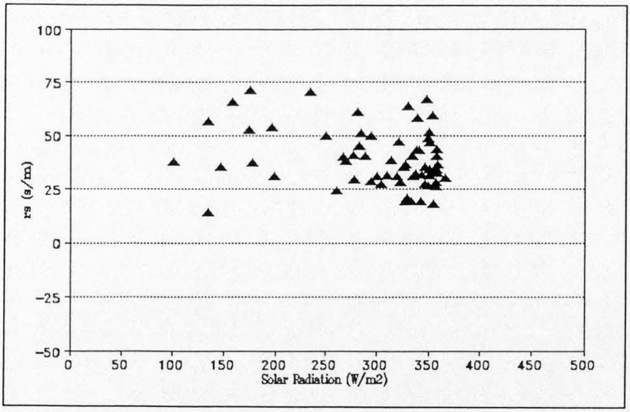

FIGURE C17. Computed Daily Surface Resistance versus Solar Radiation (Winter Wheat, 1978).

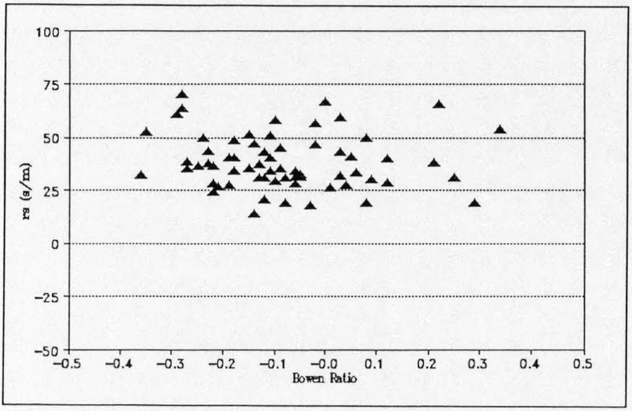

FIGURE C18. Computed Daily Surface Resistance versus Bowen Ratio (Winter Wheat, 1978).

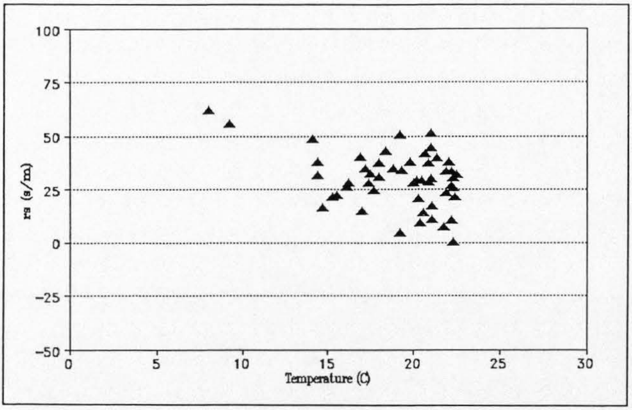

FIGURE C19. Computed Daily Surface Resistance versus Temperature (Spring Wheat, 1979).

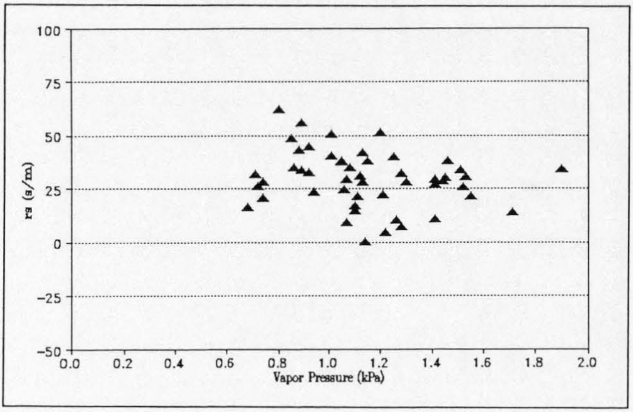

FIGURE C20. Computed Daily Surface Resistance versus Vapor Pressure (Spring Wheat, 1979).

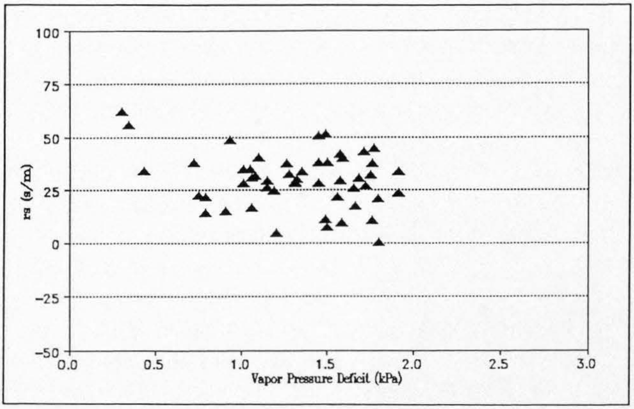

FIGURE C21. Computed Daily Surface Resistance versus Vapor Pressure Deficit (Spring Wheat, 1979).

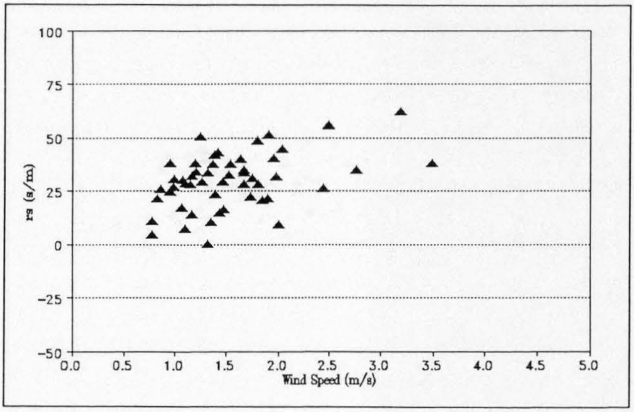

FIGURE C22. Computed Daily Surface Resistance Versus Wind Speed (Spring Wheat, 1979).

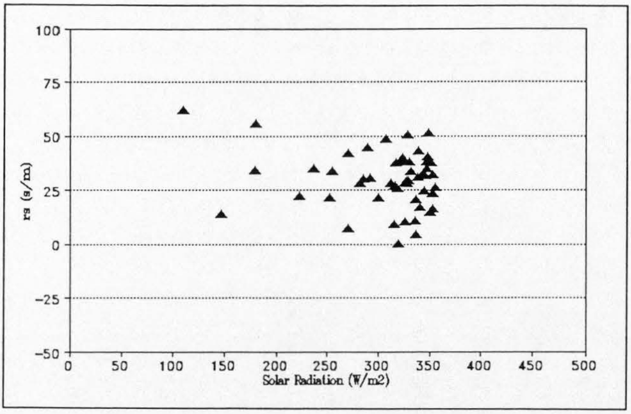

FIGURE C23. Computed Daily Surface Resistance versus Solar Radiation (Spring Wheat, 1979).

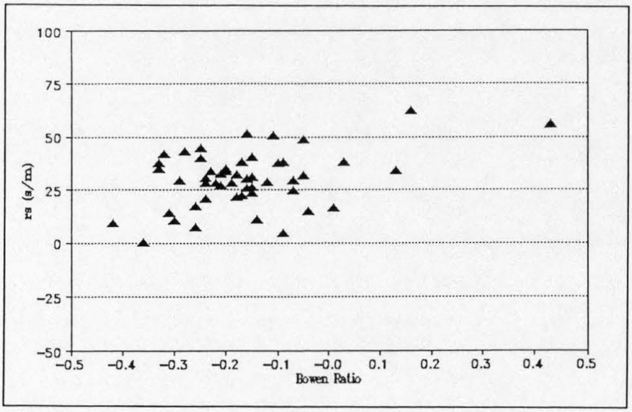

FIGURE C24. Computed Daily Surface Resistance versus Bowen Ratio (Spring Wheat, 1979).

VITA

Paul J. Vanderkimpen

Candidate for the Degree of

Doctor of Philosophy

Dissertation: Estimation of Crop Evapotranspiration by means of the Penman-Monteith Equation.

Major Field: Agricultural and Irrigation Engineering

Biographical Information:

Personal Data: Born in Ronse, Belgium, June 29, 1963, son of Jacques and Jeannine Vanderkimpen.

Education: Graduated from Our-Lady-of-Lourdes High School, Edegem, Belgium, in June 1981; received Ingenieur degree (equivalent to Master of Science) in Agricultural Engineering from the Catholic University Leuven, Leuven, Belgium, in July 1986; received Postgraduate degree in Hydraulic Engineering from the International Institute for Hydraulic and Environmental Engineering, Delft, The Netherlands, in September 1987; completed the requirements for the Doctor of Philosophy degree in Irrigation Engineering at Utah State University, Logan, Utah, in August 1991.

Awards and Honors: Fellow of the Commission for International Cultural Relations (Belgium), 1986-87; Fellow of the Belgian American Educational Foundation (Belgium), 1987-88; recipient of a Research Vice President Fellowship, Utah State University, 1990-91; member of Phi Kappa Phi, National Honor Society.

Professional Experience: Research Assistant, College of Agricultural Engineering, Catholic University Leuven, July 1986 through August 1986; Research Assistant, Department of Agricultural and Irrigation Engineering, Utah State University, July 1988 through June 1991.

Affiliations: Phi Kappa Phi;
Royal Flemish Engineers Association;
American Society of Agricultural Engineers;
American Society of Civil Engineers.